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PLAN OF RESEARCH FOR INTEGRATED SOIL MOISTURE STUDIES

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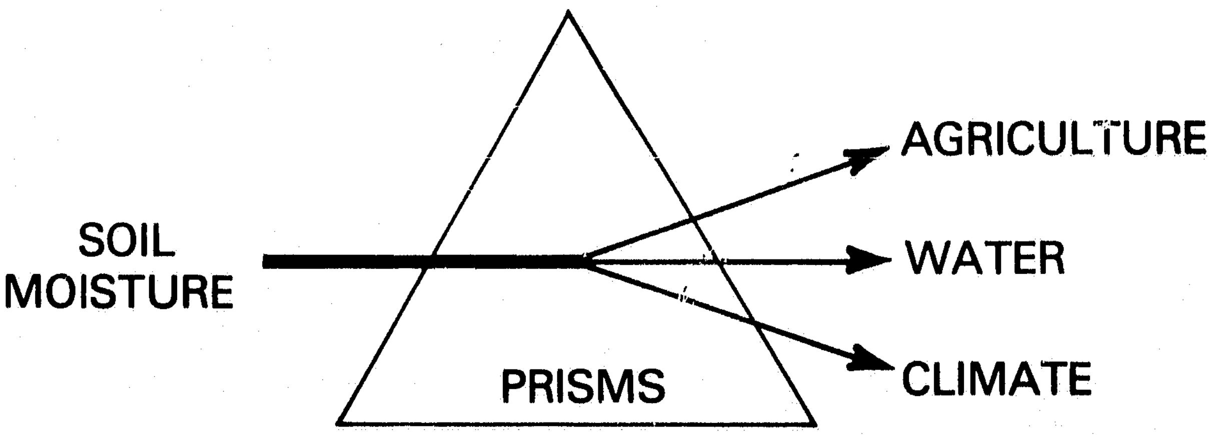
Plan of Research for Integrated Soil Moisture Studies



The Soil Moisture Working Group

NASA
National Aeronautics and Space Administration

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PREFACE

Soil moisture information is not an exclusive requirement of agriculture, hydrology, or weather and climate. Rather, it is an important parameter for applications in each of these three discipline areas. Research in remote sensing has shown that soil moisture measurement using multispectral data is definitely possible, but much fundamental research is yet to be done. Because it is felt that this fundamental soil moisture research is common to each discipline area, an integrated approach to soil moisture and remote sensing investigations is advocated. Based on recommendations generated at the Soil Moisture Workshop held at the United States Department of Agriculture (USDA), Beltsville, Maryland in January 1978, a Soil Moisture Working Group was established to coordinate and develop an integrated plan of research. The Plan of Research for Integrated Soil Moisture Studies (PRISMS), which will guide the National Aeronautics and Space Administration (NASA) effort through Fiscal Year 1986, is not a static document. Research results will be periodically reviewed by the Working Group and revisions to PRISMS will be made as new concepts and techniques are developed. If PRISMS is successful, user demonstration projects and the orbiting of optimized soil moisture sensors can be accomplished by the mid-1980s. Subsequently, comprehensive soil moisture data for operational purposes could be available by the late 1980s. If these goals are realized, the authors of this plan will feel that they have played a small but important role.

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PLAN OF RESEARCH FOR
INTEGRATED SOIL MOISTURE
STUDIES

EXECUTIVE SUMMARY

Soil moisture information is a potentially powerful tool for applications in agriculture, water resources, and climate. At present, it is difficult for users of this information to clearly define their needs in terms of accuracy, resolution and frequency because of the current sparsity of data. But it is the consensus of users that once an operational program for acquiring soil moisture information is developed, numbers of users and applications will increase. In addition, as more soil moisture information is acquired and evaluated, they will be better able to specify their observational requirements. As a result, this research plan will most likely need successive iterations as more information becomes available.

This plan describes NASA's research program; however, several other agencies, including USDA and NOAA are interested in developing the capability to obtain soil moisture information with remote sensing techniques. The high cost of remote sensing research makes it imperative that NASA, USDA, NOAA and others work together toward this common goal. With a cooperative effort, this ancillary information can be developed to assist agricultural, hydrologic and climate resource interests. The research specified in this plan will be led by NASA research centers and will be conducted both in-house and through extensive cooperation with university researchers and government scientists. Figure 1 shows the integrated effort for soil moisture planning and implementation. Input is received from the various user communities in order to specify the research plan, PRISMS. Research and testing covered by the plan is implemented through the following programs: the Joint Program for Agriculture and Resources Inventory Surveys through Aerospace Remote Sensing (AgRISTARS); Water Resources Applied Research and Data Analysis (ARDA); and Climate ARDA. Techniques developed in the program are tested and fed back to the users for evaluation and further modification.

The objective of this plan is to define and conduct an integrated and coordinated research effort to develop and refine remote sensing techniques which will determine spatial and temporal variations of soil moisture and to utilize soil moisture information in support of agricultural, water resources, and climate applications. The soil moisture requirements of these three different application areas have been reviewed in relation to each other so that one plan covering the three areas could be formulated. Four subgroups were established to write and compile the plan, namely models, ground-based studies, aircraft experiments, and spacecraft missions.

MODELS

Models have several important roles in the study of soil moisture using remote sensing. There are two categories of models that are involved: User Group Application Models, and Research Models. User Group Application Models are the decision-making tools of various agencies. These models can help define the type of soil moisture information that remote sensing should provide. Research models are used to understand the phenomena of soil-water-plant-atmosphere interactions, electromagnetic wave-soil moisture interactions and to extend limited data sets. Other models serve several purposes including relating soil moisture to the remotely sensed data.

If remote sensing is to be of any value in the measurement of soil moisture, several model-related problems need to be resolved. The procedures and models employed by user groups must be understood. These models will define the types of measurements that must be provided. The research program should first try to satisfy the current needs of the user group models. Following this, there should be investigations conducted to determine how these models might be adapted to better utilize remotely sensed measurements. More importantly, we should devote significant effort to the development of new models particularly suited to using the soil moisture remote-sensing capabilities. One aspect of the new model development should be a means for extrapolating the near-surface layer soil moisture available from remote sensing to greater depths in the soil profile, e.g., through the root zone.

The general philosophy of the working group was that the model studies were extremely important and the results should be used to guide and plan the ground-based, aircraft, and future spacecraft missions. Close cooperation must be maintained so that pertinent results from the modeling studies can be input to the planning of field experiments on a timely basis, and so that experimentally obtained data, on the other hand, can be used in model verification.

GROUND-BASED STUDIES

In addition to supplying data necessary for the development of soil moisture models, the ground-based experiments serve two other important functions. First, the truck-mounted systems can be used to determine the effects of varying soil, vegetation, and moisture parameters on the remote sensing of soil moisture in controlled field experiments. To accomplish this, a procedure for the soil moisture experiments and a set of specific studies have been formulated. Second, by using a variety of sensors, the results from such studies can be used to specify the optimum sensor combination to use for aircraft or space missions. It was recognized that in order to do this, all existing truck systems should be outfitted with both a multifrequency passive and active microwave capability as well as thermal infrared and visible sensors.

AIRCRAFT EXPERIMENTS

It was felt that the major functions of the aircraft program would be first to extend the soil moisture data base beyond what is possible with a ground-based system. While ground-based systems offer the best experimental control, they are extremely limited in measuring the spatial variability of soil moisture and a range of varying en-

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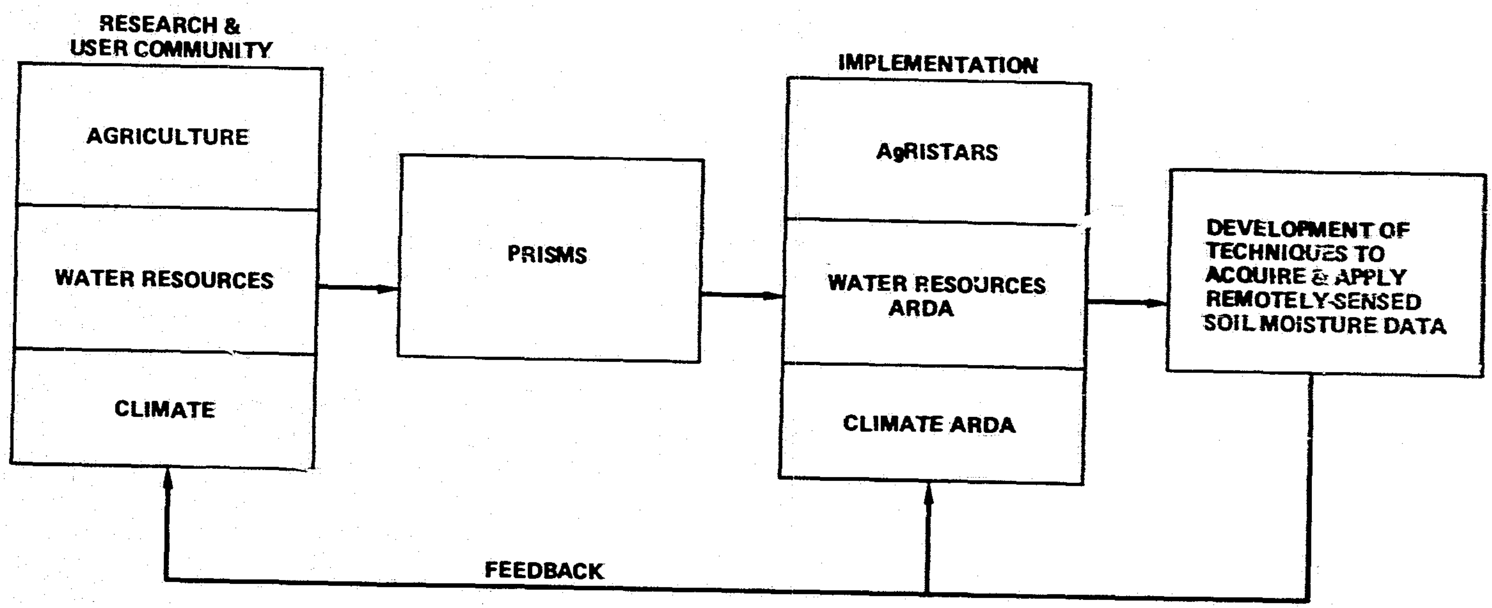

PRISMS - Plan of Research for Integrated Soil Moisture Studies

ARDA - Applied Research and Data Analysis

Figure 1. Integrated Soil Moisture Planning and Implementation.

vironmental conditions. Aircraft can be used to add this dimension to the ground-based data sets. Secondly, the aircraft program, because of these capabilities, can be used to provide additional and more widespread testing and verification of the application models. Finally, the aircraft platform is the logical test bed for the simulation of spaceborne system capabilities. Optimum sensor configurations as determined from modeling and ground-based studies can be verified and modified when using aircraft. The airborne approach is thought to be ideal for simulating the temporal and spatial coverage that will eventually be available from space, and is called for in several of the soil moisture experiments proposed.

SPACECRAFT MISSIONS

Although, in this plan, no resources are devoted to the development of hardware for, or the launching of spaceborne soil moisture missions, it is proposed that there be a major effort in the development of the mission concepts. A two-phased approach to a soil moisture space data source is proposed as follows:

Phase I - The first step would be a satellite in an HCMM-type orbit launched in the mid to late 1980's. It would carry a sensor similar to the Advanced Very High Resolution Radiometer (AVHRR) to provide thermal infrared and visible data. Additional sensors would be an L-band radiometer plus the possibility of a C-band radar or additional passive bands as part of a multichannel radiometer.

Phase II - It is expected that research results from the first mission will permit the development of definitive mission requirements for Phase II, as well as an optimized definition of sensors and their parameters, i.e., spectral bands, spatial and temporal resolutions for both active and passive sensors, depression angles and polarizations.

SPECIFIC EXPERIMENTS AND RESEARCH TASKS

It was felt by the working group that certain specific experiments and research tasks should be performed in conjunction with the procedures discussed in the modeling, ground-based studies, aircraft experiments, and spacecraft missions sections. The experiments include emphasis on extension of techniques for remotely estimating soil moisture developed in arid and semi-arid regions to humid regions. Results from analysis of the remotely sensed soil moisture data in the humid areas will be compared to previous results from semi-arid areas. Effort should also be expended on an experiment to acquire areal soil moisture data with remote sensing and compare it to conventional point soil moisture measurements, rainfall distribution patterns, and gamma ray soil moisture data. The objective would be to emphasize the capability of remote sensing to adequately characterize the spatial soil moisture status. In order to demonstrate the temporal remote sensing capabilities, an experiment is proposed to collect and analyze a complete set of multispectral data for an entire growing season for various crops. Such an experiment should be performed in an area with detailed temporal ground truth and dedicated aircraft support. Two experiments to directly supplement the major areas of the plan are proposed. First, a detailed ground-based study of factors affecting soil moisture determination in different geographic regions using multispectral sensors is called for. Parameters considered include soil roughness, soil texture, moisture profile, vegetation cover, and snow cover. Secondly, a user applications model experiment should be vigorously pursued. This would involve work with other agency scientists to test soil moisture remote sensing methods for their particular applications. The results of such an experiment will lead to a better understanding of the remote sensing input specifications as well as provide a starting point for the development of new models.

The working group has identified the research tasks necessary for supporting this plan. These are listed under the five major emphasis areas of modeling, ground-based studies, aircraft experiments, spacecraft missions and user test programs. A few additional efforts are listed under other tasks. These tasks have all been scheduled in the time frame of the next six years (detailed schedule given under Program Schedule and Experiments). The first two years of the program will be devoted to fundamental research to better understand the physical processes involved. The next two years will emphasize experiments and validation of the models. Results will be used to update the models in preparation for use in the final phase of user testing which will cover the last two years. User experiments will be started during this phase for eventual testing of the soil moisture technology in an operational mode. Final revision of models for applicability to user problems will be included in this phase.

GOALS

The specific goals of this program are:

- Determination of remote sensing capabilities
  - expected accuracy of the measurement in the presence of realistic surface conditions
  - a specification of the actual soil moisture sampling depth.
- Definition of possible sensor combinations for performing this measurement from either aircraft or spacecraft platforms.
- Development of models for using this remotely sensed information to obtain moisture profile and evapotranspiration estimates.
- Determination of the spatial and temporal scale of the measurements to satisfy the applications requirements and to be consistent with the naturally occurring variability.

SUMMARY

This document provides the guidelines to be followed in conducting NASA soil moisture research. Certain experiments and research tasks are necessary in modeling, ground-based studies, aircraft experiments, and spacecraft missions. The plan will be periodically reviewed by the working group and updated as necessary to reflect significant research results. The research will be best accomplished through cooperation between NASA researchers and other government agency scientists and university investigators.

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INTRODUCTION

The responsibilities of providing adequate food and fiber for future generations, while conserving our soil, water, and air resources, is of great concern to our national leaders and scientists. If we are to meet these responsibilities, the precision of our prediction capability has to be improved.

There is a delicate balance between the supply of and the demand for essential food and fiber. This balance is so delicate that the normal variability of climate can upset it, especially in extreme years. We will continue to have periods of excess rainfall which will be randomly interrupted by periods of rainfall deficiency.

A combination of low farm prices and drought can be disastrous. The "Dust Bowl" days of the Thirties are an important part of American history. The current unrest among farmers stems from low farm commodity prices and uncertainties associated with drought conditions similar to those of the Thirties.

Variability in precipitation accounts for the recent large irrigation development in this country. Irrigation gives the farmer and the banker security. Although only about 10 percent of the cultivated land in the U.S. is irrigated, about one-fourth of our gross agricultural income is from these lands. Every drought results in the drilling of additional irrigation wells and the depletion of reservoir water. Large-scale well development is responsible for the groundwater mining that has occurred in this country. The fact that agricultural demands account for 85 percent of the overdraft is causing the urban population and politicians concern. Every indication suggests that the competition for water between the rural and urban communities will become more intense.

Because of an adequate supply of surface and ground water in the recent past, agriculture has not made the most efficient use of the water resource. Specialists in the field estimate that irrigated crops benefit from only about half of the water applied. The competition for water and the overdraft on our groundwater resources make imperative the more efficient use of water by agriculture in the future.

Excess water can also upset the balance in our food and fiber production. Many of our serious plant diseases are prevalent during wet periods. Excess rainfall during the ripening stage and harvesting of our feed grains can reduce crop yields and quality appreciably. The wet period late in the 1977 season in Canada and the Northern Plains caused reduced wheat yields and poor quality. An appreciable portion of the 1977 corn crop in the Southeast could not be marketed because of aflotoxins. (Aflotoxins develop when the crop is subjected to prolonged wet periods after the grain has matured.)

Yield on lands with poor surface drainage can be seriously reduced by crop inundations. In addition, yields are frequently reduced because of delayed planting on poorly drained lands. High rainfall at planting time also causes most of the erosion that occurs on these lands.

There is a real need for a better understanding of how too much or too little moisture affects crops at their different phenologic states. The accuracy with which we can predict how too much or too little water will affect crop yields depends largely on how well we understand the interaction of soil water and plants. Better techniques are urgently needed for relating the impact of water stress or excess water on crop yields. When these relationships are understood, they can be reduced to a mathematical model. The effectiveness of these models must then be confirmed by field data and the use of tools like remote sensing.

Soil moisture is the critical variable in all crop prediction models. It is basic to yield estimation, runoff prediction, erosion forecasting and irrigation scheduling. Farmers schedule field operations based on soil moisture conditions. Agribusiness uses regional soil moisture data as a tool in developing their plans for the movement of fertilizer and pesticides.

Although measuring soil moisture by remote sensing seems to be feasible, there are specific problems to be considered. Albedo measurements can be used to delineate the three classical stages of soil drying, but use of this technique is limited to the surface of bare soil. The monitoring of soil surface temperature has also shown good correlation to near-surface soil moisture, but the presence of vegetation significantly reduces application of this technique. However, the assessment of crop stress by a combination of canopy temperature and albedo measurements appears to have great potential for predicting crop yields by remote sensing in this situation. This technique utilizes the innate ability of the plant as a soil moisture measuring device. Possibly the greatest potential for remote sensing lies in the use of multispectral systems using frequencies ranging from the visible light through the microwave region. These possibilities, along with the use of temporal data, have not been sufficiently studied due to the lack of adequate truck-mounted and aircraft systems.

Microwave technology appears to be useful for measuring near-surface soil moisture. Besides the all-weather capability of the microwave systems, the strong dependence of the dielectric properties of soils on their moisture content at microwave wavelengths affects the soil reflectivity and emissivity. These quantities can be remotely sensed with active microwave (radar) and passive microwave (radiometry) techniques. Microwave approaches also have the capability of sensing the soil through a moderate amount of vegetative cover, which extends their utility. Numerous experiments have shown the responses of these sensors to be strongly correlated with the moisture in a layer about 5 cm thick. There are several additional factors which contribute noise or uncertainty to the extraction of soil moisture information from the microwave responses. In addition to vegetative cover, these include surface roughness and shape, soil variability and soil temperature. The quantification of these effects is an early objective of this research effort.

This plan describes NASA's research program for developing this potentially powerful agricultural, water, and climate management tool. Several other agencies, including the USDA and NOAA are inter-

ested in developing the capability to obtain soil moisture information with remote sensing techniques. The high cost of remote sensing research makes it imperative that NASA, NOAA, USDA and others work together toward a common goal. With a cooperative effort, this urgently needed tool can be developed to assist agricultural, hydrologic and climate resource interests. The research specified in this plan will be led by NASA research centers and will be conducted both in-house and through extensive cooperation with other government agency scientists and university researchers.

OBJECTIVE

The objective of this plan is to define and conduct an integrated and coordinated research effort to develop and refine remote sensing techniques which will determine spatial and temporal variations of soil moisture and to utilize soil moisture information in support of agricultural, water resources, and climate applications.

SOIL MOISTURE INFORMATION REQUIREMENTS

Soil moisture information is of significant value in a number of applications. Much of the user community, however, can be identified as potential rather than present users of soil moisture information because of the current absence of data. It is difficult for users to clearly define their needs in terms of accuracy, resolution, and frequency. But it is the consensus of users that once an operational program for acquiring soil moisture information is developed, numbers of users and applications will increase. In addition, as more remotely-sensed soil moisture information is acquired during research and evaluated by users, we will be able to better specify the remote sensing user requirements. As a result, this plan will most likely need successive iterations as more information becomes available.

Three important criteria in providing soil moisture information are timeliness, accuracy, and adequacy of coverage. Many users, when asked about their requirements of these criteria, will reply that they need the information as accurately and rapidly as possible with updates every few days. When the user is questioned about the specific utilization of the data, some important aspects become apparent that should be considered when developing data acquisition systems.

Most users like to be alerted to deviations from the expected or the normal as soon as possible. Initial announcements need not be extremely accurate, but warning of a problem is important. This is especially true for crop conditions, low water supplies, changing temperatures and other potential problems that affect many users. Therefore, timeliness of information is more important initially than accuracy.

After the warning of a problem, refinement of a specific answer should begin. Most users are quite tolerant of a week's time in obtaining that refinement. Decision makers are already looking at a number of options and will make the decision on which option to follow when specific data have arrived or when a point has been reached where a decision must be made.

Measurements or estimates of surface soil moisture alone are thought to be of limited value to agriculture. Data are needed for depths of at least one meter and preferably two meters. This is the zone of maximum root concentration and therefore water uptake by the plant. Water resources users, however, can be significantly helped with estimates that are related to moisture in the top 5 to 20 cm of the soil. Surface layer soil moisture possibly can be used to infer the moisture at deeper depths as an alternative technique pending development of more sophisticated systems.

Drought

We know that a deficiency in plant-available soil moisture reduces crop production, but precise definition of drought is difficult. There have been definitions of drought for nearly every discipline and it is usually defined in terms of how it affects a specific discipline.

An agricultural drought is concerned with soil moisture deficiencies related to crop yield. This varies depending upon the crops and the climatic region where they are grown. If irrigation water is available, the economic impact of drought will be reduced. Drought conditions in dryland farming regions are the major cause of agricultural crop losses while drought in irrigated regions usually results in excessive use of water to produce a crop; conversely, drought may result in less area under cultivation in any given year.

A hydrologist will think of drought as a deficiency in precipitation or runoff. He may consider this in terms of a decline in groundwater levels or in the amount of water held in a reservoir. The measurement will usually be in terms of a deviation from the normal, a relationship which is found in most definitions.

A meteorological drought will be concerned with a deviation from the normal or mean precipitation for that location. Systems or indices such as the Palmer Drought Index have been used to classify drought severity using the difference between actual monthly precipitation and that required to meet the demands of evapotranspiration. Both the duration and the magnitude of the abnormal moisture deficiencies are considered.

A drought becomes recognizable only after a period of time has passed. The termination of a drought is almost as difficult to detect as the beginning because it may be temporarily interrupted by one or more short precipitation periods. A knowledge of soil moisture at any given time, by location, becomes extremely important when discussing drought and determining its potential and actual impact.

Agriculture

Soil moisture, as mentioned earlier, is important to the growth of all vegetation. Soil moisture is considered directly or indirectly by many different users in each stage of production of cultivated crops, range, and forest. Agricultural crops must have optimum soil moisture regimes to reach maximum production. Drought or excessive moisture deviations from those optimum levels will reduce imme-

diate and future yield, increase possible damage and losses from pests, and may result in the complete loss of the crop.

Crop Production

Soil moisture in the root zone is needed on a daily basis with global coverage to support the operation of crop yield and crop calendar models.*

During the growth and development stages, the farmer or producer is concerned with a number of practices which he uses to stimulate the growth, quality and yield of his crop. Some of these practices include fertilization, water management, which includes both irrigation and drainage, and cultivation and/or harvesting operations. The control of pests such as weeds, insects or pathogens has fostered a number of industries which not only supply the chemicals but also custom apply them for the producer. All of these management practices are related to the soil moisture conditions because soil moisture determines when the practices are most efficient.

Data and information requirements for soil moisture are variable at the different production stages (Table 1). Highest accuracies are required for yield estimates, irrigation scheduling, and pest control. More frequent coverage at a higher resolution is required when greater economic gains or losses are at stake.

Leaching of soil nutrients, deposition of saline or alkaline deposits, and flushing of agricultural chemicals in surface runoffs are of concern because of their impact on the environment. Movement of herbicides, fungicides, and insecticides within the soil water is also a direct economic concern to the farmer. More accurate soil moisture measurements would assist in better planning to reduce losses.

Range Production

Some of the same practices or production stages listed in crop production are of interest to range managers and to wildlife managers. The range manager should be concerned with the problems of erosion and soil damage which can result during ground preparation and planting phases if the soil is too wet (soil compaction, puddling, etc.) or too dry (wind erosion).

Range and wildlife managers may use a number of techniques such as timing of herbicide application to control poisonous or noxious plant species. Deferred grazing is used to prevent compaction damage to wet soil to permit the germination of desirable species. Practices such as salting, fencing, and water improvements are used to distribute grazing more evenly.

*Identified by the Joint Remote Sensing Planning Team during the March 13-17, 1978 Planning Sessions at Goddard Space Flight Center, Greenbelt, Maryland.

Table 1
Soil Moisture Information and Data Requirements
at Different Crop Production Stages

Crop Production Stage	Accuracy Level*	Frequency (Days)	Resolution (km^2)	Depth
Planning (Acreage & Yield Predictions)	3-5	7-20	1-15	profile
Ground Preparation & Planting	1-3	5	.5-1	surface layer
Germination	3	5	1-10	surface layer
Growth & Development				
Nutrient Supply	3	7-10	1-10	profile
Water Management-Irrigation	5	3	.5	profile
Water Management-Drainage	3	3-5	1-10	profile
Pest Management	5	3	.5	surface layer
Maturing-Yield Estimate	3-5	3-10	.5-1	profile
Harvest	3	3-7	.5	surface layer

* 1 = General accuracy of High, Medium, or Low
2-4 = Gradation between accuracy level 1 and 5
5 = ±4% accuracy by value measurement

Forest Production

Many aspects of the production stages listed under crop production will also apply to timber production. The forester is concerned about soil moisture conditions suitable for ground preparation and planting twice in one crop cycle. Seedlings are frequently grown in nurseries where the nurseryman faces problems in seedbed preparation and adequate soil moisture conditions for germination and seedling survival. A few years later the seedlings are transplanted. In suitable terrain, planting of the seedlings is a mechanized operation involving trafficability problems for tree planters.

The forester may not only irrigate and fertilize in his nursery, but will also apply pesticides to control competing brush, weed trees, insects, and diseases. Applications must be timed to critical periods in the life cycles of the pests, which are frequently dependent on soil moisture temperature and plant phenological stage.

Pest Management

Some pests follow a life cycle that depends on soil moisture and temperature conditions. Altering these conditions to any extreme will disrupt their life cycle. The effect of shallow water bodies and the increase of mosquito production and its effect on public health is a familiar one. The increase of the screwworm and its effect on cattle production in the Southwest is an example of concern for animal health.

A number of users are concerned about conditions which affect pest epidemiology, including the World Health Organization, Public Health Service, Food and Agriculture Organization, Agency for International Development, and state veterinarians.

In addition to farmers and chemical manufacturers and dealers, other user groups that have an interest in soil moisture information as it affects pests are the Regional and Environmental Science Centers of NOAA, a number of agencies with USDA (Animal and Plant Health Inspection Service, and Science and Education Administration), aerial applicators, and farm broadcasters.

Soil Classification

Soil moisture is an important factor in the mapping of soils and their classification. Soil moisture regimes are considered in the soil classification process. (Soil moisture regimes are defined in terms of groundwater level and the presence or absence of water held at a tension of less than 15 bars of atmospheric pressure in the root zone.)

Hydrology

The hydrologist is concerned with precipitation, runoff, infiltration, irrigation and evapotranspiration. There are many factors pertaining to the hydrologic cycle (Figure 2) that are closely related to soil moisture. The land surface and soil blocks as shown in Figure 2 affect all aspects of water movement except when the atmosphere and water bodies interact directly. Soil moisture is important because it affects runoff and the rate of infiltration, which are vital to estimation of flood hazard and the design of water control structures.

Several important stages of the hydrologic cycle were explored for their importance to users. The accuracy needs, frequency of coverage and resolution requirements of the users were estimated (Table 2).

Runoff Potential

The National Weather Service of the National Oceanic and Atmospheric Administration has the primary responsibility for flood hazard warnings. However, flood-flow measurements by the U.S. Army Corps of Engineers and the U.S. Geological Survey of the Department of the Interior are reported to forecasters to aid in the warning system. Current methods of runoff prediction depend on adequate separation of the precipitation into infiltration, runoff, and surface storage. This separation is dependent on the soil moisture condition at the time the storm begins.

The Soil Conservation Service of USDA is responsible for design of large numbers of water control structures on ungauged drainage basins. Their models require accurate estimates of soil moisture or antecedent precipitation as an index of soil moisture. Forecasts of runoff from ungauged watersheds can be improved with reliable estimates of soil moisture. These models are used to establish design criteria for dams, bridges, culverts, and channel control devices. Improvement in the prediction capability of the models will result in improved design that can save construction costs and improve water quality. Further benefits may accrue from the use of time series soil moisture measurements to classify runoff potential on ungauged areas.

Erosion Losses

Estimation of erosion and sedimentation transport is a primary concern of design engineers. When present techniques are used, sediment yield is attributed to soil losses from fields and from bank erosion and gullies. Moisture conditions in the soils affect the weathering processes and the ultimate supply of sediment to the stream. However, the runoff process, which is affected by soil moisture, is the primary mechanism for erosion and sediment transport. Unfortunately, present design procedures have not been developed to the point where soil moisture is used in calculating erosion and transport primarily due to the lack of adequate soil moisture estimates.

Measurement of soil moisture combined with remote sensing data that measure the extent of gully area could enhance the prediction of sediment transport into the water storage structures and sediment traps. The need for production control is primarily in the upstream drainage systems. Builders of dams for flood detention or power supply are very concerned with predicted volumes of sediment. Sediment transport is also a concern to those responsible for water quality since pesticides are transported by sediment particles.

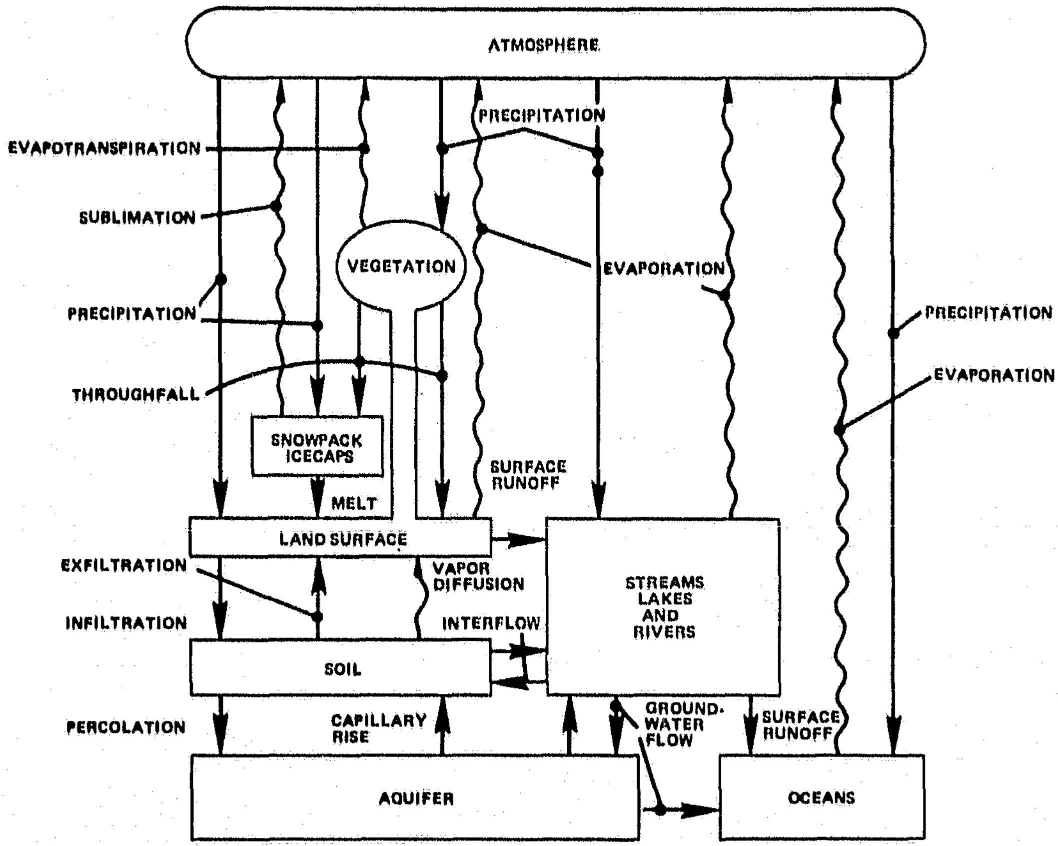

Figure 2. The Hydrologic Cycle from an Engineering Viewpoint (after Eagleson, 1970).

Table 2
Needs of Soil Moisture Information and Data Requirements in Hydrology

Soil Moisture Applications and Identified Users	Accuracy Level*	Frequency (Days)	Resolution (km^2)
Runoff Potential:			
Federal Users: NOAA-NWS, USACE, SCS design engineers, WPRS, HUD Flood Insurance Program	1**	3-7	5-25
State Users: Highway Departments and Water Resources Centers			
County and City Governments			
Private Power Companies			
Erosion Losses:			
Federal Users: Design Departments of USACE, USDI and USDA-SCS	3	3	5-25
County Organizations of Governments	5	3	.5
Farmers Organizations	3	3	1
Reservoir Management:			
Federal Users: USACE, WPRS	1	3-7	5-25
State and Local Users: Water Resources Centers	3	3-7	.5
Private Power Companies, regional planners, recreation industries	3	3-7	.5
Infiltration for Trafficability and Structure Design			
Federal Users: USACE, USDA-SCS	5	3	.5
State Users: Drainage Districts, Planners	5	3	.5
Private irrigation design engineers, mining engineers, developers	5	3	.1
Water Quality			
Pesticide and Nutrient Losses:			
Federal Users: EPA, FDA, USDA-SCS	5	3	.1
State Users: Water Resources Centers	3-5	3	.1-.5
Private irrigators, farm organizations, feed lot operators, hydrologic engineers, planners and developers.	1-3	3-7	5

* 1 = General accuracy of High, Medium or Low
2-4 = Gradation between level 1 and 5
5 = ±2% accuracy by volume measurement
** = Data refer only to the users on the respective line in the table

Reservoir Management

Reservoir management models depend on runoff models that calculate inflow to the impoundment. Improvement in water runoff prediction with additional soil moisture data will improve the management mode but new models that can incorporate soil moisture data must be developed. The allotment of the water for specific uses is very dependent on the amount of water in the reservoir and that which can be predicted.

Infiltration

Infiltration rate or rate of depletion of surface soil moisture is a critical soil interpretation used by those developing irrigation systems, predicting watershed runoff, determining groundwater recharge, etc. These rates must be known before any water balance model can be updated effectively. Almost all infiltration models have one or more parameters that are dependent upon the soil moisture before water application. Drying rates also determine how early soils can be subjected to tillage or heavy traffic. Time series of soil moisture measurements can be used to help determine these rates.

Water Quality

Water quality monitoring and management are the responsibility of many federal agencies with the Environmental Protection Agency (EPA) setting the standards to be followed. The agencies must seek EPA's approval of proposed work that may influence water quality. The movement of water in soils can transport pollutants and nutrients into the groundwater supply. Modeling soil water movement requires a reliable measure of soil moisture. It should be mandatory that soil moisture measurements be related to more than one depth level in order to develop more precise models.

Most water quality analysis depends upon runoff from the land surface or percolation out of the root zone. The influence of soil moisture here is indirect through its control of the rate of runoff. However, soil moisture does have a direct influence on the rate of the mineralization of nitrogen which can affect efficiency of nitrate fertilizer applications. Excess fertilizer may end up as a pollutant in a waterway or the groundwater.

Wetland Inventory

The U.S. Fish and Wildlife Service has begun an inventory of wetland and aquatic habitats of the United States. Detection and measurement of water and soil moisture are extremely important to the wetland classification system. When an adequate sensor system can be defined for measurement of soil moisture, an absolute classification of wetlands may be accomplished.

Weather and Climate

Evapotranspiration is the combined loss of water through the process of evaporation and transpiration. Many methods exist for calculating or measuring evapotranspiration; a compilation of the various techniques is given in a treatise by Jensen (1975). Evaporation occurs from water surfaces or bare soil while evapotranspiration occurs when a canopy is present on the surface.

Idso et al. (1974) described the various stages of evaporation from a bare soil surface. During the first stage when the surface is wet, the rate is limited only by the availability of energy to the surface. As the surface dries, the rate decreases and is controlled by the transfer of water to the surface. The length of time between stage 1 and 3 evaporation depends on the surface soil moisture and the energy available to the surface. Therefore, the rate of soil evaporation depends upon the soil moisture content.

Evapotranspiration from a canopy depends on the soil moisture available in the volume of soil occupied by active roots, the type of canopy, and the energy input to the system. There are only a few methods which accurately determine evapotranspiration with limited water availability (Jensen, 1975; Kanemasu et al., 1975). Soil moisture controls the rate of water supply to the roots, but the canopy controls the rate of water loss to the atmosphere through stomatal regulation.

Of the evapotranspiration models that are available, few are applicable over large regions and make use of remotely sensed data. Research is needed in the following areas:

- Spatial variability of soil moisture in the field and its effect on the integrated evapotranspiration for the field
- Evapotranspiration models which are applicable to large regions
- Experimental procedures for defining the spatial and accuracy requirements

The accuracy and spatial resolution requirements vary for each application. For individual fields, the accuracy of soil moisture may have to be 2 to 3% (volume basis) for the upper two meters of the soil profile and the spatial resolution on the order of 25 to 100m. For large regional applications, the accuracy may be relaxed to 5 to 10% (volume basis) for the upper two meters of the profile and the spatial resolution to 100 km.

Numerical simulation studies with atmospheric general circulation models show that the storage of water in the soil and its transfer to the atmosphere by evapotranspiration has a large influence on rainfall.

An example is the set of simulation experiments by Charney (1977), shown in Figure 3, where in one case the land surface evapotranspiration was made almost zero everywhere and, in the other, it was made either equal to or some large fraction of the potential evapotranspiration, with all other conditions being exactly the same.

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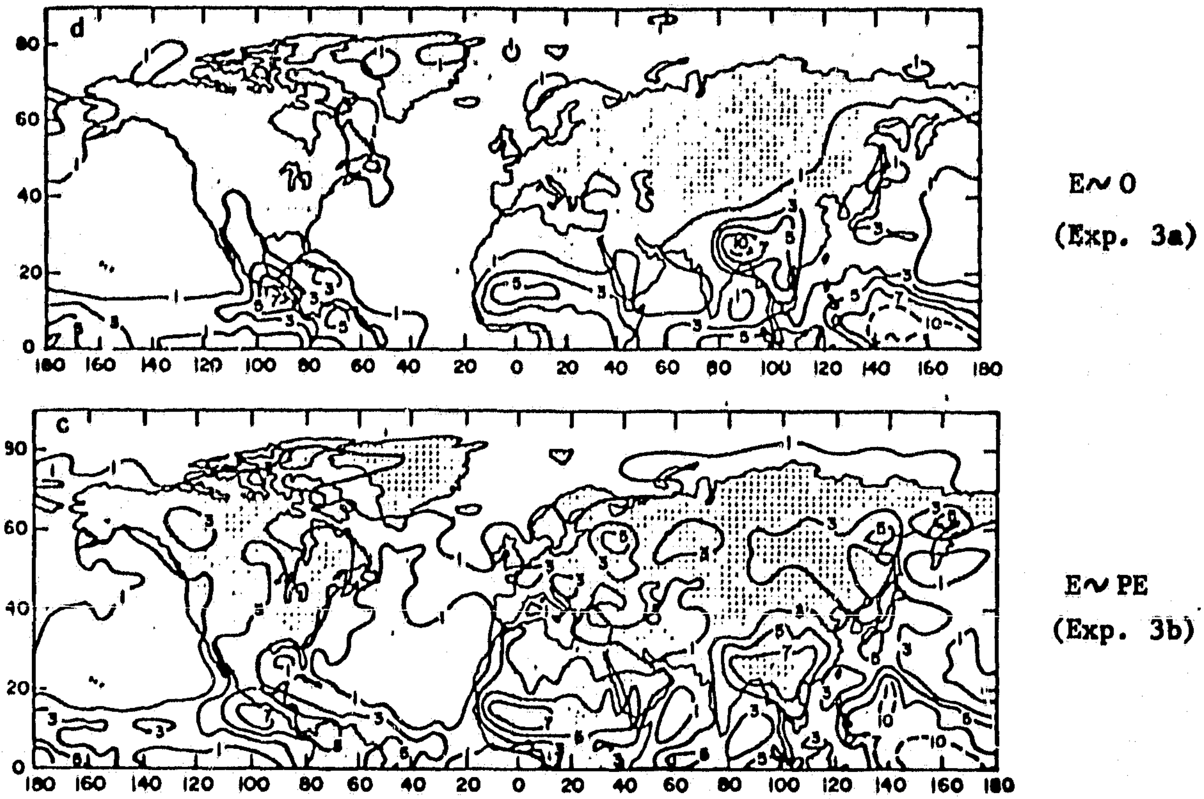

Figure 3. Simulated July Mean Precipitation (mm/day), from Charney, et al. (1977).

As the figure shows, when there is no land surface evapotranspiration, there is relatively little rainfall on the continents, and the rain that does fall is mainly what comes out of the oceanic monsoon currents.

In another set of experiments, by Rowntree and Bolton (1978), an interactive rather than a fixed ground hydrology was used. The maximum available water that the soil could hold was set equal to 20 gm cm^{-2}, and the ratio of evapotranspiration to potential evapotranspiration was taken as the lesser of unity and [soil water/10 gm cm^{-2}]. Three simulation experiments were made, each for 50 days ending on July 15, in which the only difference was the initial amount of water in the soil at those land points in Europe which lie between 40° and 54°N, and west of 30°E.

In Figure 4, the top panel shows the simulated rainfall, averaged over the final 30 days, when at all land points the initial soil water was 5 gm cm^{-2}. The center panel shows the rainfall when, within the indicated region, the initial soil water was zero. The bottom panel shows the rainfall when, within that region, the initial soil water was 15 gm cm^{-2}.

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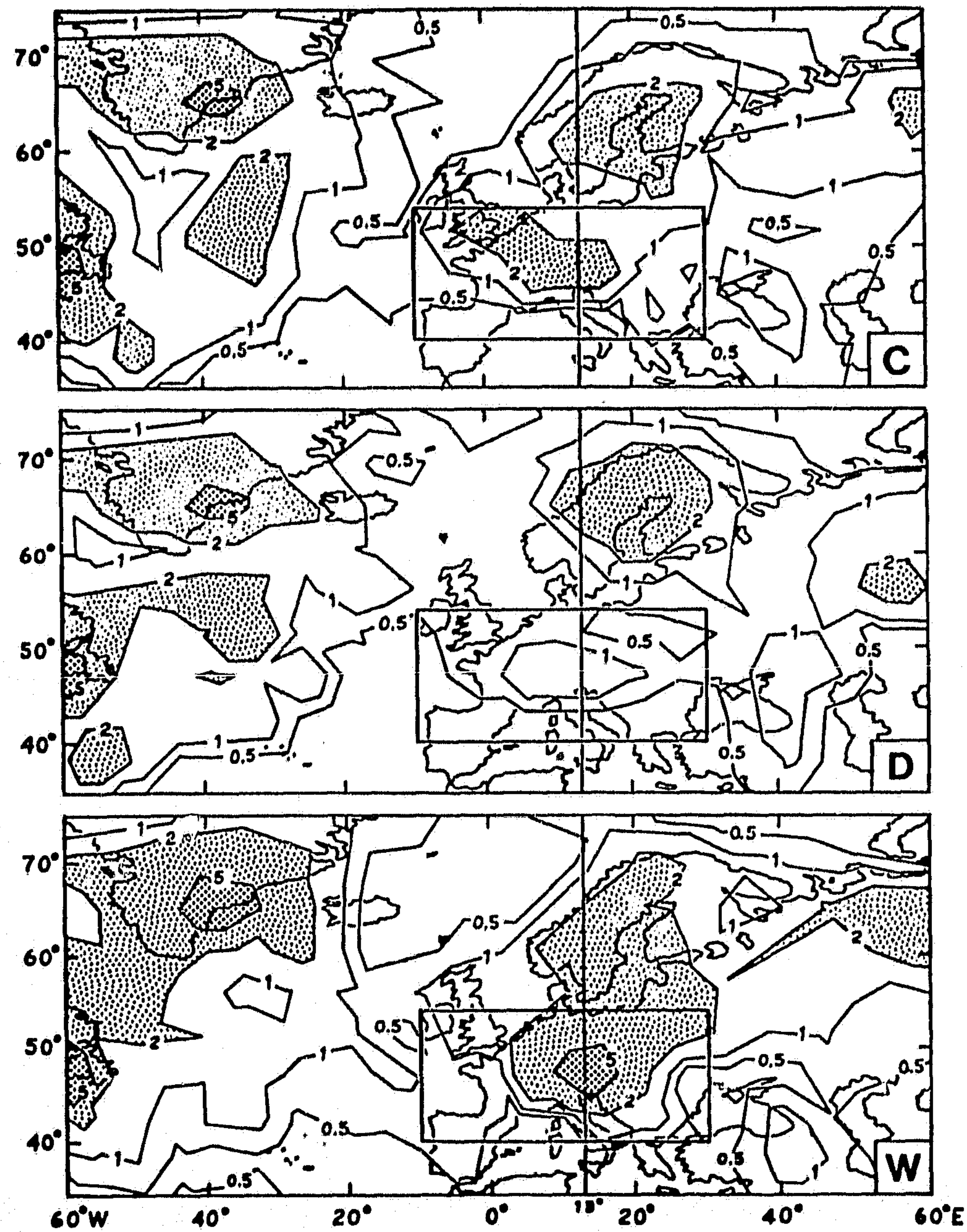

Figure 4. Rainfall (mm/day), Averaged for 15 June - 15 July, in the Simulation Experiments of Rowntree and Bolton (1978). Top panel: Control run (C), in which the initial soil water, on 27 May, was 5 gm/cm^2 everywhere. Center panel: Dry soil experiment (D), in which, within the indicated rectangular region, the initial soil water was 0. Bottom panel: Wet soil experiment (W), in which, within the indicated rectangular region, the initial soil water was 15 gm/cm^2.

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Figure 5 shows the profiles of the rainfall, along longitude 13°E, for the three cases. We see that over most of the map the differences in the rainfall are such as can be produced by the natural variability of the atmosphere. But within and immediately to the north of the region of different initial amounts of soil water, there is a large increase in the rainfall when the initially wet soil case is compared with the initially dry soil case. At the center of the region, the 30-day average rainfall increases from about 1 mm/day to 5 mm/day.

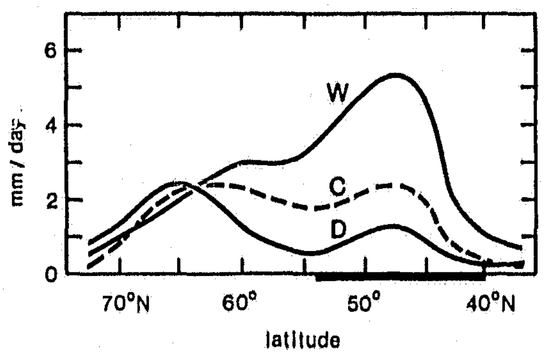

Figure 5. Meridional Distribution of the Rainfall, Along 13°E Longitude, in Experiments C, D and W.

These two sets of experiments are for the summer season, when the solar radiation is large and, therefore, the surface radiation balance and the potential evapotranspiration are large.

In the winter season, the surface radiation balance and potential evapotranspiration will be smaller and, therefore, the actual evapotranspiration will generally be smaller. Moreover, in the winter season some of the soil water that enters the air will be removed from the continent as part of the process by which cold, and therefore dry, continental air begins its conversion into warmer and moister tropical air. We do not expect, therefore, that there will be as much precipitation recycling of the soil water in winter as in summer.

FOREIGN USES OF SOIL MOISTURE INFORMATION

The economy of the United States is tied very loosely to that of other developed nations, and with many important and long-range trade aspects of developing nations. Soil moisture information can be utilized in similar ways in other developed nations as has been discussed for the United States. In developing nations, the importance of soil moisture data is in the prediction of current food production and assistance in agricultural land development.

The importance of accurate weather predictions and soil moisture supplies has been recognized by such projects as the Large Area Crop Inventory Experiment (LACIE). The initial planning phases of any project of land development require reliable data on soils, vegetation, water and other resources. Current reliable data also have an influence on the location and method of infrastructure development.

Since the passage of the Title XII Act of 1976, U.S. Land Grant Colleges have taken a more aggressive and realistic role in foreign agricultural development. The need for planning information, including soil moisture status, would be extremely helpful to these programs as well as to ongoing programs of foreign governments, Food and Agricultural Organization, Agency for International Development, foundations and private development financiers.

AGENCY/ORGANIZATION USES

Following are summaries of uses of soil moisture information and activities related to soil moisture that were submitted by various agencies and organizations:

Forest Service

The Forest Service uses soil moisture information in three major areas:

- Soil moisture as related to plant growth
  - time of planting for forest regeneration, range seeding, etc.
  - species selection
  - site productivity
- Soil moisture and hydrologic relationships
  - predicting soil runoff, flood and erosion hazard
- Soil moisture and soil mantle stability relationships
  - road construction and other engineering activities

In all three areas the Forest Service needs the ability to determine and/or predict the soil moisture content at a given time. At present soil moisture regimes, identified by direct moisture measurements, are used to make such predictions. Because on-site measurements are costly and time consuming, the Forest Service more often estimates soil-moisture regimes on the basis of the type of natural vegetation on the site.

Economics, Statistics, and Cooperative Service

Soil moisture is undoubtedly very important in its effects on crop yields. The Economics, Statistics, and Cooperative Service has a definite interest in soil moisture because the agency estimates and forecasts crop yields. At maturity, crop yields can be measured and estimated directly from sample surveys. Forecasts, when crops are approaching maturity, can also be based upon direct crop measurements as "interpreted" through appropriate forecasting models. Use of physiological models which incorporate soil moisture among other variables are therefore of greatest potential value in providing early to mid-season forecasts. Currently several physiological models are being evaluated. All depend to some extent on soil moisture. If the utility of any of these models is

proven, and if they are adopted as an operational method, more comprehensive soil moisture information can be utilized.

Soil Conservation Service (SCS)

The Soil Conservation Service is interested in soil moisture as it relates to drought and soil classification. To aid rural drought disaster or potential drought areas, SCS needs improved knowledge of soil moisture. If SCS could deliver useful information on the spatial extent of drought conditions and probable future moisture availability, better resource management decisions could be made.

The principal drought-related needs of SCS are:

- A system for drought forecasting that allows the government time to gear up with assistance programs
- A signal whereby SCS can adjust its operation to focus on drought-related assistance

Soil moisture needs of SCS related to soil classification are:

- Water content at saturation by family
- Saturated and unsaturated hydraulic conductivity by family

Some present and proposed soil moisture studies include:

- A study to determine moisture status and temperature of dry soils in the southwest, in order to determine the length of time the soils are dry, as an aid in classification
- A study of the physical properties of soils in watershed hydrology
- A survey conducted by the National Soil Survey Laboratory to study effects of paralithic contacts on hydraulic conductivity
- A planned soil moisture study in eight of the major agricultural regions in the United States to verify and improve soil moisture models for determining and evaluating wetness and drought, and to improve soil classification with respect to moisture regime
- An agreement with the Science and Education Administration to expand a site-specific watershed evapotranspiration model to an area-wide evapotranspiration model

Science and Education Administration (SEA)

The Science and Education Administration is interested in soil moisture because of its importance to:

- Physiological processes of crop and range plants that affect growth and yield
- Irrigation requirements and scheduling
- Drought, drainage needs, trafficability, habitat of insects and pathogens
- Land suitability and capability
- Water yield
- Watershed hydrology and management
- Non-point source pollution

Water and Power Resources Service (WPRS)

The Water and Power Resources Service (formerly U.S. Bureau of Reclamation) requires soil moisture and related information for wide-area application of its Irrigation Management Services (IMS) program. The goal of IMS is to achieve optimum operation of entire irrigation projects. The IMS program currently includes portions of 26 irrigation projects in 12 western states and involves field-by-field irrigation scheduling and operational coordination of farm water demand throughout irrigation project storage and distribution systems. Several functions are performed periodically (daily, biweekly, etc.), including monitoring soil moisture with neutron probes, tensiometers or similar equipment; computerizing water budget analysis of evapotranspiration and consumptive use; and accounting of irrigation and cropping patterns. Soil moisture and related information needed for application of IMS include:

- Identification of land mass receiving irrigation
  - total irrigated vs. nonirrigated acreage
  - crop identification and acreage
  - field boundary mapping
- Surface moisture conditions (indication of recent irrigation or precipitation)
- Crop growth stage
- Cultural operations (periodic harvesting of alfalfa)
- Identification of areas of crop stress
- Identification of drainage problem areas and high water tables

The Hydrology Branch of the Division of Planning Coordination has the following soil moisture and related requirements:

- The ability to identify farms and fields receiving irrigation water
- Coverage, depth, and water equivalent of snow
- The soil moisture condition of a drainage area prior to snow coverage
- The soil moisture condition of a drainage area before and after a precipitation event
- The soil moisture condition of a drainage area before and after a flood
- The soil moisture condition of a field at the beginning and end of a growing season

- The soil moisture condition of irrigated fields at the head and lower ends after irrigation

The Land Utilization Section of the Resource Analysis Branch is interested in soil moisture because of its importance in economic land classification for sustained irrigation. Planning studies for water and land resource development include determining moisture retention properties, infiltration characteristics, and permeability conditions of soil. In addition to direct soil moisture considerations, land classification is also concerned with related conditions of soil salinity, root penetration, and aeration within the root zone.

U.S. Geological Survey (USGS)

The Water Resources Division of USGS is conducting several research studies that include soil moisture as a variable. Although soil moisture needs are somewhat peripheral to most of the water resource investigations, a number of hydrologic studies require soil moisture information. Current activities related to soil moisture are:

- A study of the dynamic movement of water from the soil surface to an aquifer. The hydraulic characteristics of the soil types and the availability of the water to move through the soils are of primary concern.
- A study devoted to development of groundwater supplies and soil and water conservation for public land. If the degree of soil wetting or moisture depletion can be determined synoptically and at frequent intervals, the information would be useful for management decisions on use of resources of the arid west.
- Development of model for runoff analysis. Volume and timing of surface runoff from rainfall or snowmelt are influenced by soil moisture conditions immediately preceding the event. These antecedent soil moisture conditions vary temporally and spatially, and include factors such as slope, aspect, soil type, and vegetation type and density.
- A study of erosion and sedimentation.
- Wetlands studies. Although wetland soils are often saturated, some fringe areas may be dry during certain times of the year, and these dynamic conditions may be important in understanding wetland hydrology.
- National water-use inventory. The Water Resources Division has been directed to conduct a national water use inventory that includes domestic, agricultural, and industrial uses. One of the more difficult aspects of the inventory is identification of irrigated areas.
- A study of water movement in karst terrain and fracture zones. Remote sensing, particularly thermal imagery, has been used to identify sink areas in karst terrain, and to study water movement through fracture zones.

Army Corps of Engineers

The Waterways Experiment Station of the Corps of Engineers is interested in soil moisture monitoring and forecasting because soil moisture has a major influence on performance of different types of military vehicles and is a factor in estimating stream levels and predicting flooding. For military application, estimating soil moisture without recourse to in situ field measurements is desirable.

In the late 1940's the Waterways Experiment Station (WES) began studies on mobility of military vehicles. It was obvious that soil moisture to a depth of about 12 inches had a major influence on soil strength and vehicle mobility. Mobility studies are still underway and it appears that reasonably accurate forecasts of soil moisture will be possible utilizing a soil moisture model with information from meteorological monitoring and forecasting, and remote sensors.

Recent developments in computers, mathematical modeling and remote sensing have added a new dimension to hydrology. The Waterways Experiment Station is currently conducting a study in military hydrology which is intended to improve the hydrologic capability of the armed forces. The major difference between military and civilian hydrology concerns the restrictions on access to the watershed under military operation, making remote sensing an essential aspect of the study. It is felt that a soil moisture model compatible with remote sensing systems will be necessary to estimate moisture as a function of depth to forecast soil moisture conditions throughout the watershed for several days in advance.

Soil moisture is also one of the parameters used by the Corps of Engineers in civil works projects to predict reservoir inflow from storms as well as for general river forecasting. It is also one of the parameters used in estimating snow cover runoff. In addition, soil moisture content downstream is an input for planning reservoir operations. Data obtained by remote sensing could be used by the Corps in these operations.

Agency for International Development (AID)

AID is interested in soil moisture as it relates to drought and desertification in developing countries. Lack of rain, shifting winds, and overgrazing are among the factors that contribute to desertification. If the drought that affected the Sahel in Africa could have been anticipated, arrangements could have been made earlier to supply and distribute food to the affected areas. Thus, AID is interested in development of remote-sensing techniques to anticipate the need and supply food to drought-affected areas. Soil moisture is one of the parameters that is important in drought monitoring.

NASA

As part of a LACIE-type program, NASA is interested in improving yield technology through soil moisture sensing. At the present time the capability exists to run some soil moisture budget models using ground meteorological data. What is needed is an improvement over the current state of the art. Soil moisture estimates are required not only

for bare soil, but for a developing canopy as well. Preliminary agriculture yield model/soil moisture requirements are as follows:

- Soil moisture profile measurement requirements
  - resolution between field size and (15 km)^2 grid
  - water content to within ±10 percent of value with specifica n of depth of water
  - depth of profile to beneath root zone
  - repeat every 18 days to update soil moisture models to more frequent repeats if dictated by integration with yield models
  - soil moisture yardstick invariant through crop season, canopy, tillage variations, topographic difference, time of day
- Detailed requirements are being developed through assessments of performance of competing yield modeling approaches.

NASA, in response to the Interdepartment Committee for Atmospheric Sciences' report A United States Climate Plan, has developed a plan for using NASA observational capabilities to advance practical understanding of the behavior of climate systems. The climate spectrum has been divided into four separate but interrelated portions:

- Current state of the climate
- Regional climate which occurs on a time scale longer than a month but shorter than a decade
- Climate which occurs on time scales of a decade or longer
- Climate produced by man's activities on all time and spatial scales

The ability of the soil to store water and release it through evapotranspiration is important in climate forecasting. Soil moisture requirements of the NASA Climate Program are summarized in Table 3.

Table 3

Soil Moisture and Related Requirements of the NASA Climate Program*

Parameter	Desired Accuracy	Base Requirement	Spatial Resolution	Temporal Resolution
Surface soil moisture	$0.05 \frac{cm^3\ H_2O}{cm^3}$ soil	4 levels	500 km	1 month
Soil moisture (root zone)	$0.05 \frac{cm^3\ H_2O}{cm^3}$ soil	4 levels	500 km	1 month
Evapotranspiration	10%	25%	500 km	1 month
Plant water stress	stress/unstressed		500 km	1 month

*These are preliminary estimates which will be refined as soil moisture parameters are incorporated in evolving climate models, and sensitivity experiments are performed.

NOAA

There are several reasons why NOAA is interested in soil moisture remote sensing. First, because NOAA is responsible for river and flood forecasting and soil moisture is an unknown, unmeasured variable that affects such forecasts; secondly, because NOAA has an obligation to the agricultural community to provide improved agricultural-meteorological-hydrological forecasts and warnings; and thirdly, because NOAA has a need for soil-moisture data on global and regional scales for improved global dynamic climatological modeling and other related climate studies.

Indicative of NOAA interest in improving these three areas of study is the recent USDA/NOAA/NASA Agricultural Initiative for FY-80, the NWS Flash Flood Initiative of FY-79, and the new Climate Program established during 1978.

Currently, in the NWS river forecast models, a parameter that has served for decades is the API (Antecedent Precipitation Index). It is based on prior precipitation and provides an index number that is indicative of soil moisture.

Accurate, near-surface soil moisture values would be an improvement over the API. Operational hydrologists, however, cannot be expected to make such a change without convincing, supportive evidence. Experiments to analyze, compare, and evaluate satellite-derived soil moisture values as a function of precipitation, satellite estimation of precipitation, and API are desirable.

Kern County Water Agency (Example of a Local Agency)

The Kern County Water Agency in Kern County, California, has cooperated with various universities and organizations in evaluation of phenomena related to soil moisture, particularly in evaluating problems related to drainage. Some of these studies and activities are:

- Monitoring development of perched water tables
- Evaluating crop damage within drainage problem areas
- Landsat-aided evaluation of water demand
- Radar study of soil moisture
- Thermal study to establish surface thermal properties and soil moisture profiles
- Landsat evaluation of crop stress and crop damage.

SUMMARY OF CURRENT STATUS

MODELS

Models have several important roles in the study of soil moisture using remote sensing. There are two categories of models that are involved: User Group Application Models and Research Models. User Group Application Models are the decision-making tools of various agencies. These models can help define the type of soil moisture information that remote sensing should provide. Research models are used to understand the phenomena of soil-water-plant-atmosphere interactions, and electro-magnetic wave-soil moisture interactions, and to extend limited data sets. Other models serve several purposes including relating soil moisture to the remotely sensed data. New models may be necessary to fully exploit the capabilities of remote sensors based on sensor response.

Application Models

Agricultural Management Models

Most operational application models in agriculture which use soil moisture information are for scheduling irrigation. Several soil moisture budget models have been developed specifically for that purpose. For irrigation scheduling, profile soil moisture is required with an accuracy of ±5 to 10 percent by volume and a repeat cycle of 3 to 5 days.

These soil moisture budget models use standard meteorological data (temperature, precipitation, applied irrigation water, solar radiation, etc.) and estimates of crop growth (crop coefficient, leaf area index) to assess evapotranspiration (ET) which, along with hydraulic properties of the soil, are used to evaluate soil water depletion. Irrigation water is applied when the depletion reaches a critical value.

The Jensen et al. (1971) model is used extensively by the Irrigation Management Services (IMS) of the Water and Power Resources Service. The Jensen model estimates actual ET from a crop coefficient and potential ET. Estimates of ET are then used in a water budget to estimate soil water depletion. From these calculations an estimate of available soil moisture is derived.

A number of sophisticated soil moisture models have been developed for a variety of crops, locations and conditions (Shaw, 1963; Baier and Robertson, 1966; Shanholtz and Lillard, 1970; Lewin, 1972; Jensen et al., 1971; Fitzpatrick and Nix, 1969; Makkink and van Heemst, 1975; Kanemasu, 1977; Stuff, 1975; Stuff and Dale, 1978). These models are generally accurate, and they have been successful in estimating soil moisture profiles for the site-specific conditions for which they have been developed. Some of these models can be modified to utilize inputs from remote sensors. The Kanemasu model, which estimates soil evaporation and transpiration as separate components for use in a soil water budget, has been expanded to obtain model inputs of solar radiation and leaf area index from satellite data (Kanemasu, E. T., R. R. Stone, and W. L. Powers, 1976).

A number of growth, yield, and crop calendar models have been developed which have soil moisture as an input or have a soil moisture submodel as an integral part of the model. The models are generally research models and have not been implemented on an operational basis. Because of the Large Area Crop Inventory Experiment (LACIE), models related to wheat have received considerable attention in recent years.

The first generation models developed as part of LACIE were entirely empirical with little knowledge of the plant and soil moisture used in constructing the model. Second generation models that were developed are more physiological and many contain soil moisture profile submodels. These wheat-yield models are summarized below:

(1) Baier Spring Wheat Model (Baier, 1973)
Yield is a function of temperature, ratio of actual to potential evapotranspiration (ET)
Phenology and soil moisture submodels

(2) Haun Spring Wheat Model (Haun, 1976)
Yield is a function of a growth index and preseason precipitation
Growth index and soil moisture submodels

(3) EarthSat Spring Wheat Model (EarthSat, 1976)
Yield is a function of year, ratio of actual to potential ET
Grid cell weather, phenology, and soil moisture submodels

(4) Feyerherm Spring and Winter Wheat Models (Feyerherm, 1977)
Yield is a function of cropping patterns, variety, nitrogen and weather
Phenology and soil moisture submodels

(5) Cate-Liebig Spring Wheat Model (JSC, 1978)
Yield is a function of nitrogen, water uptake, and temperature
Phenology, water balance, and soil nitrogen submodels

(6) Kanemasu Winter Wheat Models (Kanemasu, 1977)
Yield is a function of ratio of actual to potential transpiration
Yield is a function of carbon dioxide exchange rate and leaf area index
Phenology, soil moisture, dry matter accumulation, and Landsat leaf area index submodels

Crop calendar (phenology) models which use soil moisture have been developed to predict stages of development (Haun, 1976). Growth and yield models which use either soil moisture or precipitation have been developed for other crops as well (corn, sorghum, soybean, alfalfa, etc.).

Quantitative use of soil moisture in most other agricultural applications remains a concept rather than a reality because of the lack of soil moisture information on a regional basis. Once the ability to provide soil moisture information on a regional basis is demonstrated, model development for agricultural applications will expand. Many of these assessments could be of the surface few centimeters on a high, medium, and low basis. However, the repeat cycle would be 2 or 3 days due to the dynamic nature of the surface layers.

Hydrologic Models

Hydrologic models are used for both decision making and research. Decision-making applications usually involve the prediction of the watershed response to meteorological events or the analysis of the impact of proposed watershed modifications on streamflow or other hydrologic variables.

Most of the models utilized in these studies are called continuous simulation models. The name comes about due to the fact that they perform a continuous time step accounting of the condition of the system using the current climatological inputs, the previous condition of the system, and response functions to predict the state at the end of the time step.

Most watershed simulation models include a component which simulates the soil-water reservoir. Generally, the soil column is subdivided into several layers, one of which is usually the root zone or "A" horizon of the soil. These models are set up to perform a continuous simulation of the status of the soil-water reservoir starting with a specified initial condition. The simulation time step is usually one hour.

Remote sensing of soil moisture is attractive for use with these models for two reasons. First, it can be used to bring the model simulations back in line or "recalibrate" parameters. Model structure, improper calibration and the use of point measurements can lead to errors in the model simulations. Since the model is extrapolative in nature these errors can compound. Remotely sensed measurements of soil moisture could be used to check or update the simulation. The second use of remotely sensed soil moisture measurements is as a replacement for model computations during periods of no rainfall. Models must simulate the soil moisture conditions prior to the next rainfall. If there was no rainfall for the period the remotely sensed measurements could be used for this purpose.

There are a wide variety of hydrologic models in use. Since this study is concerned with soil moisture, the review presented here deals only with those models that utilize this type of data. Single event simulation models that only require the antecedent soil moisture condition will be excluded. All of the models discussed here are continuous simulation models.

Hydrologic simulation has evolved from the use of unit hydrographs to complex watershed simulation models over the past few decades. The earlier models were lumped representations of individual hydrologic processes and spatially varied response units. Today's models are distributed linked process models.

Several surveys of state-of-the-art hydrologic models have been published (Viessman et al., 1977; Fleming, 1975). Only two models will be reviewed here: The National Weather Service River Forecasting System Model (NWSRFS) and the U.S.D.A. Hydrograph Laboratory Model (USDAHL).

The NWSRFS Model was first published by the Hydrologic Research Laboratory (1972). The model is based on the Stanford Watershed Model first introduced by Crawford and Linsley (1966). A general flow chart of the model is shown in Figure 6. Several modifications have been made to the original model and these are described by Peck (1976).

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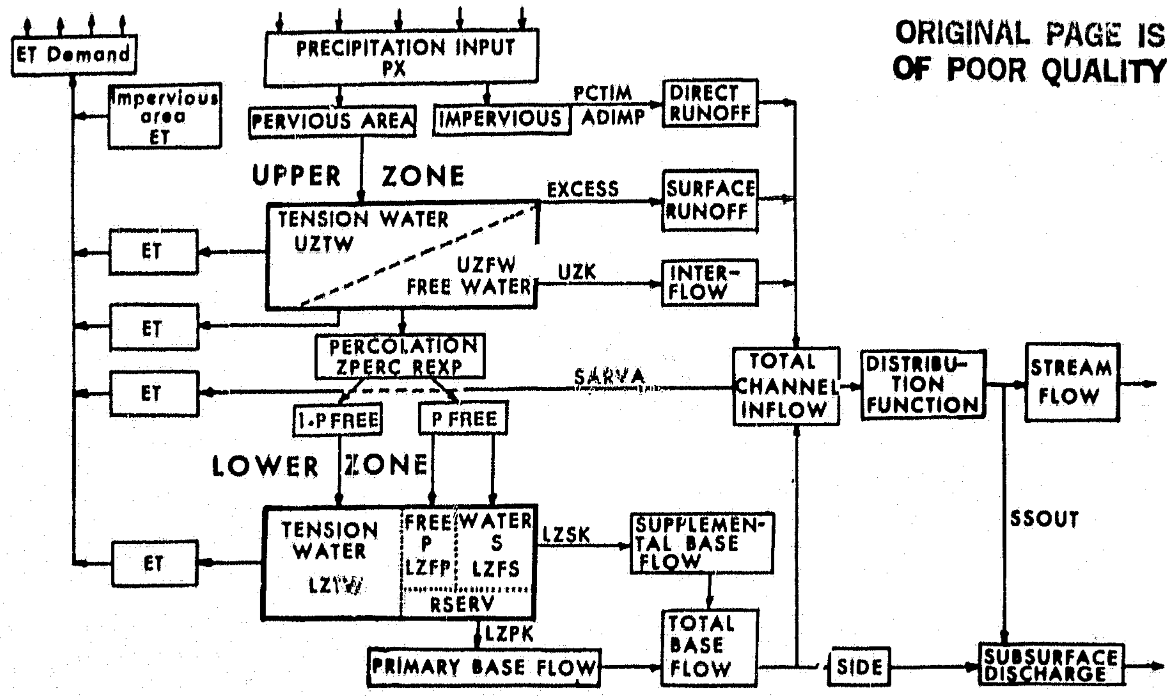

Figure 6. NWSRFS Catchment Model (Sacramento).

The soil moisture component of the NWSRFS Model is based on two soil zones. The upper zone is made up of the upper soil layer and interception storage. Lower zone storage represents the balance of the soil column and groundwater storage. Moisture is stored as either tension or free water. The model simulates these storages at each time step. A detailed discussion of the soil moisture component and its parameters is found in Peck (1976) and Armstrong (1978).

The second model, USDAHL, was developed as an aid in agricultural watershed engineering, but has proven to be very versatile in many types of land use management studies. It is described in detail in Holtan et al. (1975).

A unique feature of this model is its representation of the spatial variability of the watershed. The watershed is subdivided into homogeneous response zones. Usually the subdivision is based upon the land capability classes of the soils.

A schematic of the simulation is illustrated in Figure 7. As shown, the soil column within each zone is assumed to be the same and comprised of several layers. Generally it is subdivided into a topsoil layer and the "B" horizon. Soil moisture determination for each layer in each zone is performed on a continuous basis.

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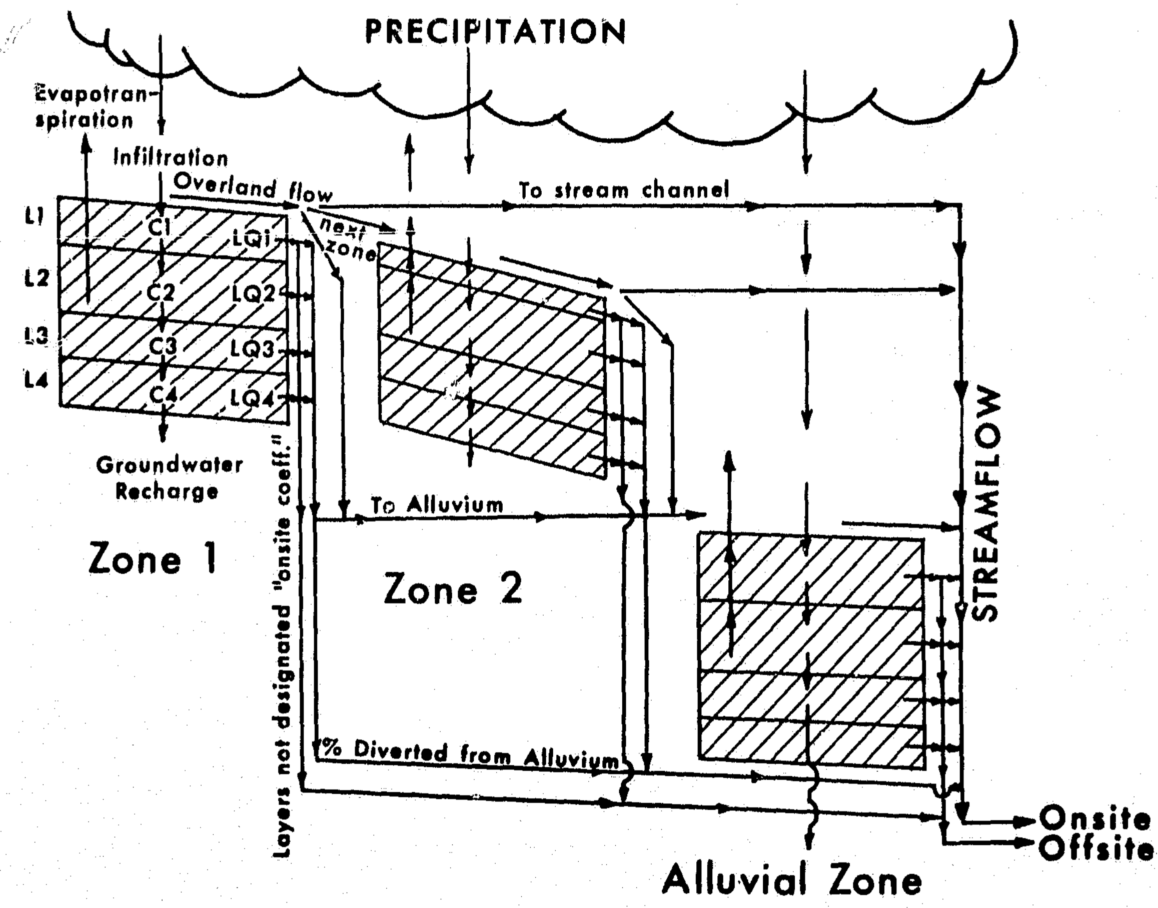

Figure 7. Zone Profiles Illustrating Hydraulic Paths to Be Indicated for Various Percentages of Outflows; Paths Greatly Influence Potential for Erosion and Chemical Transport (from Holtan et al., 1977).

Climate Models

An excellent state-of-the-art review of climate models has been prepared by JOC/GARP (1978). They state the following concerning climate models. "Physical dynamical models of the Earth-ocean-atmosphere system which determines climate are based upon the governing thermo-hydrodynamical equations for the atmosphere and the oceans, and formulations for determining the boundary conditions on the system, including those formulations for calculating the momentum, heat and water vapor fluxes across the atmosphere land surface interface. Many types of climate models may be constructed, differing in their geometry and in the manner in which physical processes are taken into account."

These models include various land surface processes. Current models utilize a simplified representation of hydrology and soil moisture and include five components; atmospheric evaporative capacity, evapotranspiration efficiency, ground temperature, soil moisture and runoff.

At the present time a great deal of research is being initiated within the field of climate modeling. The ultimate goal of this research is a model that will yield reliable predictions. Recognizing the weaknesses of the current models, investigators are examining the value of improved model structure and cell resolution.

Preliminary studies have shown that model simulations are sensitive to soil water. Thus, one way of improving model simulations would be to improve the representation of the soil water system. A number of investigators are currently adapting hydrologic models for this purpose. Generally, at least two soil layers are simulated, a shallow surface layer and a deeper layer extending to one or two meters. It is feasible that if frequent measurements of surface soil moisture were available, they could serve as a substitute for detailed hydrologic simulations.

The other relevant area of climate modeling related to soil moisture is spatial cell resolution. Many researchers feel that model simulations could be greatly improved if smaller cells were used. Because of cost and data constraints, simulations are based on very large cells generally several hundred kilometers on a side. Naturally the variability of the ground and atmospheric variables is quite high within each cell and problems arise in selection of representative parameters since there is very little data available for calibration. One way of reducing the variability is to use smaller, more homogeneous cells. However, this leads to significant drawbacks in terms of costs and data collection since all computations are multiplied by the number of cells. It is possible that frequent large area soil moisture measurements could be used as an observed variable and thus be used to calibrate the model and allow the use of larger cells.

Research Models

Research models are used to study soil-water-plant-atmospheric relationships and relationships among remotely sensed measurements and soil moisture parameters. Once the basic interactions can be modeled reliably using limited data for verification, it is possible to extend the model to other types of problems. This reduces the amount of data collection each time a new problem is encountered. Since data collection is very expensive and time consuming, research models can yield cost savings in a research program.

There are two general categories of research models: 1) soil-water movement, storage and loss and 2) electromagnetic energy-matter interactions. Many submodels and topics must be considered for the two broad model categories. The soil temperature models are dependent upon the soil-water movement models. Radiative transfer models require information from both soil-water and temperature models. Therefore, the interactions of all facets of the system must be considered in model development.

Soil-Water Movement, Storage and Loss Models

The physics of soil-water movement is well known for ideal situations. However, the physics of natural systems is not well defined due to the variability that exists. Soil-water movement is governed by physical relationships and parameters describing the media and the activity of vegetation. It is the variability of the media and the biological activities of vegetation that creates problems in modeling.

There are several texts available on soil-water modeling (Hillel, 1977; Remson et al., 1971). The text by Hillel (1977) includes computer programs. In addition, several reviews of soil-water models have been prepared (Singh, 1971; Hildreth, 1978).

Most state-of-the-art models simulate a single soil column. The column is assumed to be homogeneous in the horizontal directions. Vertical variations are accounted for by discrete layers. Each layer is considered homogeneous.

Flow between vertical layers is governed by continuity and momentum, usually expressed as a set of partial differential equations. Relationships between soil moisture and hydraulic conductivity, and soil moisture and suction are required for each layer. This requires field measurement for complete reliability. Some data are available for selected soils and matrix potentials in Holtan et al. (1968). Recently, empirical relationships based on soil texture have been developed (Clapp and Hornberger, 1978).

Simulation is performed by using finite difference approximations of the partial differentials. Increased accuracy is achieved by small time steps and narrow layers. This of course leads to increased costs for simulation and therefore, tradeoffs have to be made.

An area of current research in this area is the extension of column models to heterogeneous systems. One of the most difficult problems being addressed is the spatial variability of the soil hydraulic properties and how to incorporate them into the model without undue complexity. These problems will have great importance to programs in remote sensing of soil moisture.

Electromagnetic Interaction Models

Remote sensing of soil moisture relies on the measurement of either emitted or reflected electromagnetic energy. The wavelengths that are of interest range from the visible, where the reflectance of the soil depends on its moisture content, to the long wavelength microwave region where both the emitted and the backscattered energy depend upon moisture content. In between there is the thermal infrared portion of the spectrum (8-14 microns) where there is the coincidence of an atmospheric window with the peak of the emission from a black body at 300 K.

The modeling of reflectance and emissivity of a surface from first principles and the knowledge of dielectric properties of the medium is a very difficult task. For specular surfaces, the reflectivity and emissivity can be calculated using the Fresnel equation from electromagnetic theory. However, soil surfaces are diffuse, not specular, reflectors and the calculation of a diffuse reflectivity is in general not possible. Thus, in general, the dependences of a soil's reflectance, backscatter coefficient, or emissivity on moisture content have to be determined from experimental results.

The only situation in which specular conditions are approached is that of long wavelength (λ >10 cm) microwave measurements from smooth soil surfaces. This has been verified by the comparison of radiative transfer calculations of the expected brightness temperatures for smooth soil surfaces with field observations at a wavelength of 21 cm. However, once the surface is no longer smooth or is covered by vegetation, these effects have to be parameterized because their effect on the microwave emissions cannot be determined from first principles. In spite of this, the radiative transfer models can be useful for improving our understanding of the dependence of the microwave emission on such things as variations in the moisture and temperature profiles in the soil. Therefore, it is for the passive microwave approaches to soil moisture sensing that the application of electromagnetic theory can be most useful at the present time.

For the active microwave approach, the backscatter is determined by a combination of surface roughness and the soil's dielectric properties. It is the modeling of the backscatter from the irregular soil surfaces that is currently difficult to handle and this hampers the use of electromagnetic models to calculate the radar backscatter from soil surfaces.

For the thermal infrared approaches, the dependence of the soil's emissivity, at this wavelength (~10 microns), on soil type, soil moisture, etc., is small and therefore, the emissivity is usually assumed to be constant and close to one. The thermal infrared approach is based on the measurement of the surface or vegetative canopy temperatures. The appropriate models for these temperatures are used to relate thermal infrared measurements to soil moisture.

GROUND-BASED AND AIRCRAFT STUDIES

Classical methods of measuring soil moisture, such as gravimetric sampling and more recently the use of neutron moisture probes, have been useful for cases where a point measurement is sufficient to approximate the water content of a small surrounding area. However, there is an increasing need for rapid and repetitive estimations of soil moisture over large areas. Remote sensing techniques potentially have the capability of meeting this need. The use of reflected-solar, emitted thermal-infrared radiation, and emitted and backscattered microwave radiation, measured remotely, to estimate soil moisture will be discussed.

Physical, chemical, and electromagnetic properties of water are fundamentally different from those of dry soil materials. When water is added to soil, the properties of the resultant system change with the change in water content. In general, the amount of solar radiation reflected from the soil surface decreases with increasing water content. These changes in reflectance can be quantitatively related to the water content of the surface skin of soil. On the other hand, the amount of thermal radiation emitted in the infrared from the surface is affected by the temperature of the surface, which in turn is affected by the thermal properties of the soil/water system. Thus, a measure of emitted thermal infrared radiation is indicative of the soil moisture within the layer of soil that influences surface soil temperature. In the microwave region the emitted radiation is more strongly controlled by the change in the dielectric properties of the soil as a function of its moisture content. Similarly the radar backscatter coefficient depends on the soil's dielectric properties.

These different regions of the spectrum provide the possibility of a number of techniques for assessing the moisture content of the surface soil layers. These techniques will be described and an assessment of the current state of their capabilities will be presented in this section.

Reflected Solar

Bare Soil

Reflection of solar radiation by a bare soil surface has been shown to be influenced by the soil moisture content very near the soil surface. It is also dependent on particle size, organic matter content, surface roughness, angle of incidence and look angle. These factors combine to give tonal contrasts (Milfred and Kiefer, 1976). Reflectance also depends on soil type as well as soil moisture content (Janza, 1975). For a given soil type, reflectance decreases as the soil moisture increases due to the relative reflectance properties of water and the soil matrix. Reflectance reaches a minimum at or near saturation and remains essentially constant until about 0.1 cm of water is ponded on the surface (Blanchard et al., 1974). As the ponding depth further increases, reflectance increases because the dieletric constant for water is much higher than that for soil (Janza, 1975). However, Allen (1972) measured a minimum in reflectance at about 20 percent moisture content (near field capacity) for a fine sandy loam soil. If this is generally the case, reflectance is insensitive to soil moisture changes above field capacity.

Bowers and Hanks (1965) measured the reflectance of 0.5 to 2.5 μm radiation for two soils (a silt loam and a silty clay) at varying moisture contents in the laboratory. They found the greatest sensitiv-

ity to soil moisture for both soils to be at 1.9 μm and that reflectance increased exponentially as particle size decreased for both kaolinite and bentonite clays.

The most comprehensive field studies on the influence of soil moisture on reflectance percentage (albedo) have been performed by Idso et al. (1975). Their research, using one soil, showed three major regions of characteristic albedo variations with time, during the day after the surface soil had been wetted. The first stage is when the soil is relatively wet (volumetric water content $\theta_v > 0.20$). During this stage, the diurnal change in albedo is nearly symmetrical about solar noon, at which time the albedo is at a minimum. Albedo is higher in the mornings and afternoons than at noon because of the zenith angle. The second, intermediate stage occurs when rapid drying of the surface takes place during the day, with a color change from dark to light increasing the albedo. Finally, the third stage is when the surface has become dry ($\theta_v < 0.04$) and the albedo is again symmetrical about solar noon.

The difference in albedo between wet and dry soil is pronounced. The data also show the importance of time of day for making measurements, especially during the second stage. Idso et al. demonstrated that the effects of zenith angle could be removed through a normalizing function which was the same for wet and dry soil.

During the times of measurement of albedo, Idso et al. also measured θ_v at different depths. They averaged θ_v for different depths from the surface, ranging from 0-0.2 cm to 0-10 cm. The greatest sensitivity occurs when the 0.02 cm depth is used. Over the range of θ_v from 0.04 to 0.20 the slope is nearly constant, indicating a 0.75 change in reflectance percentage per percent change in moisture percentage. As greater depths are included in the average θ_v, the range of θ_v decreases, sensitivity decreases and data scatter increases. Although the data are from one location, they show a functional relationship between solar reflectance and moisture content very near the soil surface.

Stockhoff and Frost (1974) have shown that the degree of polarization of light reflected from a soil surface is a sensitive indicator of soil moisture changes. For completely saturated soil, i.e., free water on the surface, light reflected at the Brewster angle is totally polarized. As moisture content decreases the degree of polarization decreases rapidly. Degree of polarization is more sensitive to soil moisture change than is reflectivity. For the same moisture increase in a loam soil, the reflectivity decreased by 60% while the polarization decreased by 140%. Additional advantages of polarization are a lesser influence of roughness, partial shading, illumination, and view angle. The high amount of power available even in narrow band widths makes it possible to minimize light from sparse vegetation (Stockhoff and Frost, 1974). A disadvantage is that degree of polarization is particle-size dependent, as is reflectance.

The general conclusion for remote sensing of soil moisture of bare soils using solar reflectance is that experimental results indicate detectable differences but the development of an operational system is questionable. After extensive calibration at a specific site, it may be possible to assess surface soil moisture conditions for bare soils. Even then there would be limitations to the usefulness of the data because there has been shown little, if any, correlation between reflectance and soil moisture content a few millimeters below the soil surface. Some soil factors complicating the measurements are: (1) variations in index of refraction of the soil water due to dissolved constituents, (2) changes in the physical nature of the soil surface by the presence of water, (3) similarities in the indices of refraction of the soil and rainwater giving rise to the Christian effect (when the index of refraction of the liquid is equal to that of the sample material at some wavelength), and (4) the presence of materials, such as rocks, whose reflectance properties are different from that of the principal soil matrix (Planet, 1970). Other practical measurement problems may result from varying cloud cover, soil roughness, and vegetative cover. Using degree of polarization of the reflected light may circumvent some of these factors, but research on the approach is very limited. The usefulness of visible and near infrared techniques may increase when used in conjuntion with data from other spectral ranges.

Thermal Infrared

Bare Soil

Another component of the energy balance at a soil surface which is detectable by remote means is the longwave radiation emitted to the atmosphere from the surface. Longwave radiation is proportional to the fourth power of the absolute temperature of the surface and the "efficiency" of the radiating surface. Thus, longwave radiation measurements can be interpreted in terms of surface temperature. Two surface parameters relate to efficiency: absorptivity and emissivity. Absorptivity represents the fraction of the energy reaching the soil surface that is actually absorbed, and emissivity represents the fraction of the possible energy emitted by a body (compared to a black body). The emissivity of a body characterizes its relative efficiency as an emitter. A soil that is an efficient absorber is also an efficient emitter of radiation (Taylor and Ashcroft, 1972). This fact is important in the interpretation of remotely sensed radiation in the thermal infrared range. Emissivity for dry soils is typically greater than 0.9.

Because the intensity of emitted longwave radiation depends on the temperature at or near the soil surface, which in turn depends on soil moisture conditions, several studies have been made using infrared instruments on various platforms to measure soil surface temperatures. Soil surface temperature depends on atmospheric conditions as well as soil characteristics. The soil parameters most important in determining surface temperature are heat conductivity (k), volumetric heat capacity (C), thermal diffusivity (kC) and thermal inertia ($\sqrt{kC}$). Thermal inertia can be defined as a measure of the resistance of a material to a change in temperature, and for a soil, it is strongly influenced by moisture content. Both k and C increase with increasing moisture content, hence $\sqrt{kC}$ behaves similarly.

Due to the variation in evaporative demand of the atmosphere and variation in insolation, there normally exists a diurnal sinusoidal-shaped temperature distribution at the soil surface. Idso et al. (1975) measured surface temperatures and soil moisture content at one site to obtain the data plotted in Figure 8. The figure shows the amplitude of the diurnal wave (maximum minus minimum) at the soil surface versus water content. The results appear to be linearly distributed and independent of season. A similar linear behavior was observed with the daily difference between the maximum soil surface temperature and the maximum air temperature at about 1.5 m above the soil surface. Additional data and discussion confirming the above have been provided by Reginato et al. (1976) and by Schmugge et al. (1978), using ground and airborne based data.

Thus, two possibilities seem to exist for remote sensing of soil moisture conditions: (1) surface soil moisture can be estimated from radiometers placed on platforms to measure soil temperature differences (maximum minus minimum), or (2) they may be estimated by sensing maximum surface temperatures and using estimates of air temperatures. These approaches are commonly referred to as the thermal inertia methods.

Soil thermal inertia is a function of the thermal conductivity, heat capacity, and bulk density, which are in turn related to the physical, chemical, and mineralogical composition of the soil. Idso et al. (1975) confirmed experimentally the soil type dependence of the ($T_{s,max}$ - $T_{s,min}$) vs. volumetric water content relationship. They also found that if soil water was expressed in units of pressure potential, this dependence was minimal.

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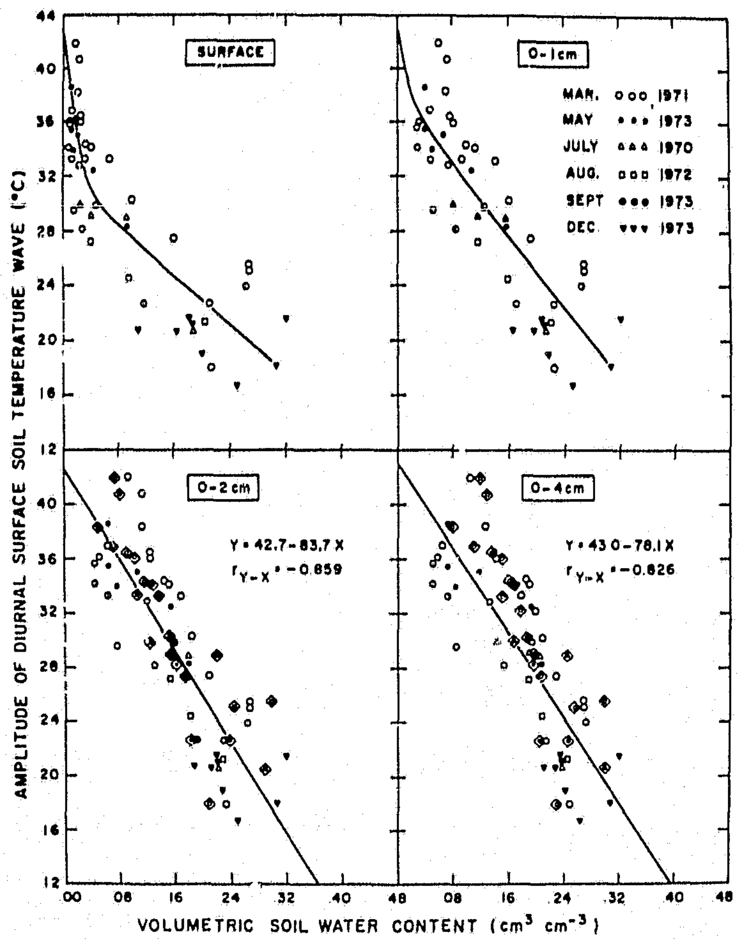

Figure 8. Summary of Results for Diurnal Temperature Variation Versus Soil Moisture. From Idso et al., 1975.

Effective depth of the estimated soil moisture conditions from temperature measurements appears to be limited to the surface few centimeters of soil. Blanchard et al. (1974) found a good correlation between temperature differences and soil moisture content in the top 5-9 cm of soil, but they surmised that the effective depth may extend to the daily solar heating depth, which is moisture content dependent but may be as deep as 75 cm. Certainly the effective depth will depend on depth stratification in soil moisture and other soil properties. As an example, Blanchard et al (1974) noted a 2-3°C change in soil surface temperatures due to an abrupt change in moisture content at 10 cm depth.

J. Cihlar, of the Canada Center for Remote Sensing, Ottawa, and Canadian colleagues have used airborne thermal scanners to estimate surface temperatures of fallow soil and then used the data to compare to measured soil moisture contents (expressed as percent of field capacity). Results confirmed the existence of an inverse relationship between the maximum minus minimum soil temperature difference versus percent of field capacity.

Vegetated Areas

Several studies have been performed to test the use of thermal scanners for assessing crop moisture stress and, hence, soil moisture conditions. Both ground and aircraft platforms have been used. Idso and Ehrler (1976) described a technique for estimating the water contents in the root zones of crops from measurements of midday leaf temperature differentials. The concept was tested for a cotton crop and two sorghum crops on Avondale loam soil. Data were collected over a two-year period. A strong correlation is shown in only a narrow moisture range (0.15-0.18). However, the method appears promising at lower water contents which is the range of interest.

Wheat canopy temperatures for a controlled irrigation experiment near Phoenix, Arizona, were used by Jackson et al. (1977) as a means of estimating water requirements. The summation of canopy temperature (T_c) minus air temperature (T_a) over time, yielded a factor termed the "stress degree day" (SDD). The SDD approach shows promise as an indicator for scheduling irrigation. A simplified evapotranspiration model using T_c-T_a and net radiation was tested against lysimeterderived evapotranspiration and the two were found to agree reasonably well (see also Idso et al., (1975).

A comprehensive study is underway in the Netherlands with the purpose of estimating regional evapotranspiration from remotely sensed crop surface temperatures (Nieuwenhuis and Klaassen, 1977; and Klaassen and Nieuwenhuis, 1977). A mathematical model, referred to as the TERGRA model, has been developed to assist in the interpretation of images of cropped surfaces (Soer, 1977). The model simulates, under specified meteorological and soil conditions, the daily behavior of crop temperature and energy balance components.

Temperatures of soybean, sorghum and millet were measured in Kansas and Nebraska by airborne (6.1 - 12.2 μm) thermal scanners to estimate evapotranspiration using a resistance model (Heilman et al., 1976; Rosenberg et al. 1975). Sizable errors (1 to 6°C) were produced by atmospheric attenuation. A correction procedure relating temperature error to atmospheric precipitable water was applied to the scanner measurements. The experimenters concluded that such a correction is essential for estimating evapotranspiration. Errors resulting from neglecting emissivity corrections were less than 1.0°C.

Rosenberg et al. (1975) used remotely sensed canopy temperatures in a resistance-type model for calculating evapotranspiration at sites in the Great Plains. Results compared favorably with those from lysimeters and the approach shows promise as a means for estimating evapotranspiration over large areas.

Summary

The above discussion indicates that the thermal infrared techniques of soil water content estimation hold considerable promise. The main task appears to be a comprehensive testing of the concepts developed in controlled ground experiments over various climatic regimes by means of aircraft and satellite measurements. These tests should yield information on the operational feasibility of the proposed concepts. In addition, limitation of these concepts should be ascertained (for example, practically all work so far has been site-specific under clear-sky conditions) to provide the basis for the choice of an optimum remote sensing method.

Microwave Approaches

Introduction

The unique dielectric properties of water at microwave wavelengths afford the possibility for remotely sensing the moisture content in the surface layer of the soil. The dielectric constant for water is an order of magnitude larger than that of dry soils at microwave wavelengths ($50 > \lambda > 1$ cm). As a result, the surface emissivity and reflectivity for the soils at these wavelengths are strong functions of its moisture content. The changes in emissivity can be observed by passive microwave techniques (radiometry) and the changes in reflectivity can be observed by active microwave techniques (radar).

Both of these approaches, active and passive microwave, have been demonstrated in extensive field and aircraft measurements. Correlations of 0.8 to 0.9 have been obtained between soil moisture in the surface layer (~ 5 cm thick) and microwave brightness temperature, T_B, or radar backscatter coefficient, σ. These microwave techniques maintain their sensitivity to soil moisture variations in the presence of a moderate crop canopy. Qualitative observations of the passive microwave sensitivity have also been made from satellite platforms at wavelengths of 21 and 1.55 cm. Thus, it appears to be possible to monitor the moisture status of the surface soil using these techniques.

Although these microwave techniques have demonstrated the capability to measure soil moisture content over a wide range of surface conditions, including roughness and vegetation cover, with a measurement precision comparable to that associated with in situ measurements, several developmental steps have to be accomplished before they can be used for global monitoring of soil moisture con-

tent. These steps may be divided into two groups. The objective of the first group of steps is to extend the experimental results to large area coverage with aircraft and spacecraft measurements. The second group of steps pertains to the requirements of the intended user of the soil moisture information. The system design specifications will be impacted by the answers to specific questions regarding spatial resolution, soil moisture depth information, and frequency of coverage, which are needed from the user community.

Soil Dielectric Properties

A number of soil dielectric constant measurements have been made in recent years as functions of moisture content, frequency and soil type (e.g. Leschanskii et al., 1971; Lundien, 1971; Wiebe, 1971; Hipp, 1974; Hoekstra and Delaney, 1974; Njoku and Kong, 1977). A compilation of some of the earlier measurements is found in the report by Cihlar and Ulaby (1974). Figure 9 shows the dependence of the real and imaginary parts of the dielectric constant as functions of moisture content as wavelengths of 1.55 and 21 cm. There is some difference between the dielectric constants measured for different soil types when plotted against moisture percent by weight especially at the longer wavelengths (Figure 9). This is due to the different strengths by which water molecules adhere to the soil particles. Thus when plotted against soil water matric potential, the dielectric constant becomes essentially independent of soil type (Newton, 1976). For this reason, brightness temperature data are often plotted as a function of percentage field capacity (which is directly related to soil water matric potential) (Schmugge, 1976). This is further desirable because matric potential (and percentage field capacity) are parameters that describe the water availability to plants and the degree of soil saturation, which are of primary importance to agriculturalists and hydrologists.

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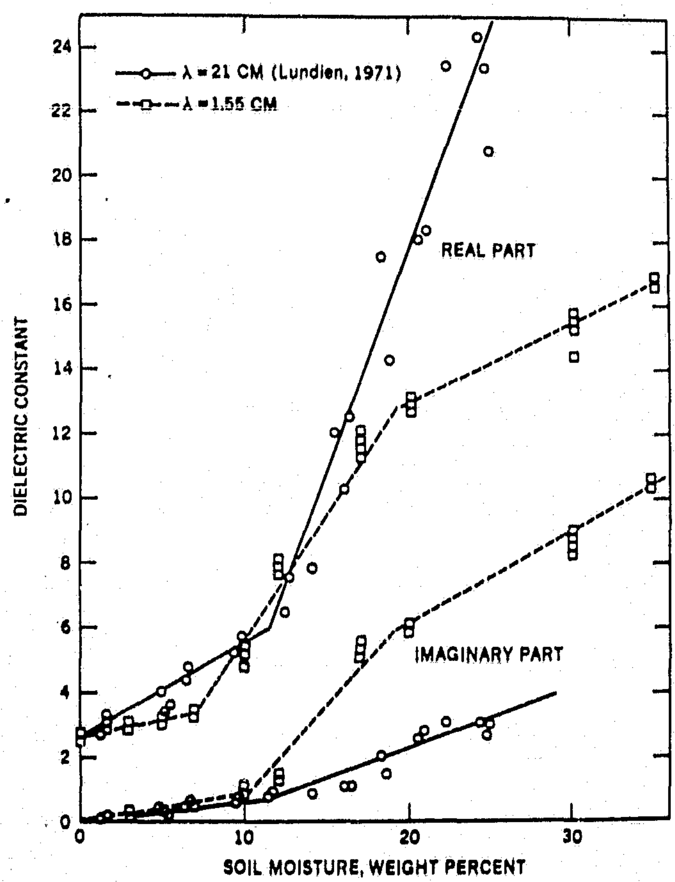

Figure 9. Dependence of the Soil's Dielectric Constant on Its Moisture Content.

The range of dielectric constants presented in Figure 9 produces a change in emissivity from greater than 0.9 for a dry soil to less than 0.6 for a wet soil, assuming an isotropic soil with a smooth surface. This change in emissivity for a soil has been observed by truck-mounted radiometers in field experiments (Poe, 1971; Newton, 1976), and by radiometers in aircraft (Schmugge, 1974) and satellites (Eagleman, 1976). In no case were emissivities as low as 0.6 observed for real surfaces. It is believed that this is primarily due to the effects of surface roughness.

As can be seen in Figure 9, there is a greater range of dielectric constants for soils at the 21 cm wavelengths. This fact combined with a larger soil moisture sampling depth and better ability to penetrate a vegetative canopy make the longer wavelength sensors better suited for soil moisture sensing.

Passive Microwave Response to Soil Moisture

a. physical basis

A microwave radiometer measures the thermal emission from the surface, and at these wavelengths, the intensity of the observed emission is proportional to its brightness temperature (Rayleigh-Jeans approximation). The brightness temperature T_B observed by a radiometer from a height above the surface is:

$$T_B = \tau \, [rT_{sky} + T_e] + T_{atm}$$

The term in brackets includes the reflected component of the downwelling sky brightness temperature (cosmic background plus atmospheric contribution) and the brightness temperature of the radiation emitted by the Earth's surface. These are modified by the transmittance of the layer of atmosphere between the surface and the radiometer. The final term in the expression is the contribution of this layer of atmosphere to the upwelling radiation reaching the radiometer. At the longer wavelengths, i.e., those best suited for soil moisture sensing, the atmospheric effects are minimal.

Thermal microwave emission from soils is generated within the soil volume. The amount of energy generated at any point within the volume is dependent on the soil dielectric properties (or soil moisture) and the soil temperature at that point. As energy propagates upward through the soil volume from its point of origin, it is affected by the dielectric (soil moisture) gradients along the path of propagation. In addition, as the energy crosses the surface boundary, it is reduced by the effective transmission coefficient (emissivity) which is determined by the dielectric characteristics of a layer close to the surface. The thickness of this layer is frequency dependent, e.g., lower frequencies are sensitive to dielectric properties at greater depths in the soil. Further theoretical and experimental work is needed to determine the dependence of the "sensing depth" on frequency and moisture profile.

The presence of soil moisture causes a marked change in soil dielectric properties, resulting in a decrease in emissivity over that of a dry soil. In addition to the presence of moisture, surface roughness and vegetation cover also have significant effects, generally tending to increase the surface emissivity.

b. ground-based experiments

Measurement programs utilizing ground-based radiometers have been performed for a number of years in a piecemeal fashion with little or no coordination between experiments.

In Figure 10a and 10b the field measurements of Newton (1976) are plotted versus angle of observation for various moisture contents and for three levels of surface roughness. The horizontal polarization is that for which the electric field of the wave is parallel to the surface and the vertical polarization is perpendicular to it. These results indicate the effect of moisture content on the observed values of T_B and the effect of surface roughness, which is to increase the effective emissivity at all angles and to decrease the difference in T_B for the two polarizations at the larger angles. Thus, by making the polarization measurements, it may be possible to separate the effects of surface roughness and soil moisture.

For the smooth field there is a 100° K change in T_B in going from wet to dry soils and it is clear that this range is reduced by surface roughness. The effect of the roughness is to decrease the reflectivity of the surface and thus to increase its emissivity. For a dry field the reflectivity is already small (< 0.1) so that the resulting increase in emissivity is small. As seen in Figure 10b surface roughness has a significant effect for wet fields where the reflectivity is larger ($\simeq 0.4$). Thus the range of T_B for the rough field is reduced to about 60° K. The smooth and rough fields represent the extremes of surface conditions that are likely to be encountered, e.g., the rough surface was on a field with a heavy clay soil (clay fraction > 60%) that had been deep plowed, which produced large clods. Therefore, the medium rough field, with a T_B range of 80° K, is probably more representative of the average surface roughness condition that will be encountered. Another important observation from Figure 10a and b is that the average of the vertical and horizontal T_B's is essentially independent of angle out to 40°. This indicates that the sensitivity of this quantity, $1/2(T_{BV} + T_{BH})$, to soil moisture will be independent of angle.

The effect of a vegetative canopy will be that of an absorbing layer that depends on the amount of the vegetation and the wavelength of observations. For a closely planted sorghum field (~ 1 m high), the sensitivity to soil moisture variation was reduced by approximately 50 percent; while sensitivity to the soil moisture variation is reduced, the correlation remains high (~ 0.9). At a shorter wavelength (2.8 cm) there is only a 10 K range in T_B in going from wet to dry. While these measurements show that a radiometer operating at 21 cm still has good sensitivity to soil moisture variations, they suggest that radiometers working at longer wavelengths (30 to 50 cm) may have better sensitivity.

c. aircraft and satellite experiments

Significant improvements in the understanding of the effects of individual scene parameters on the

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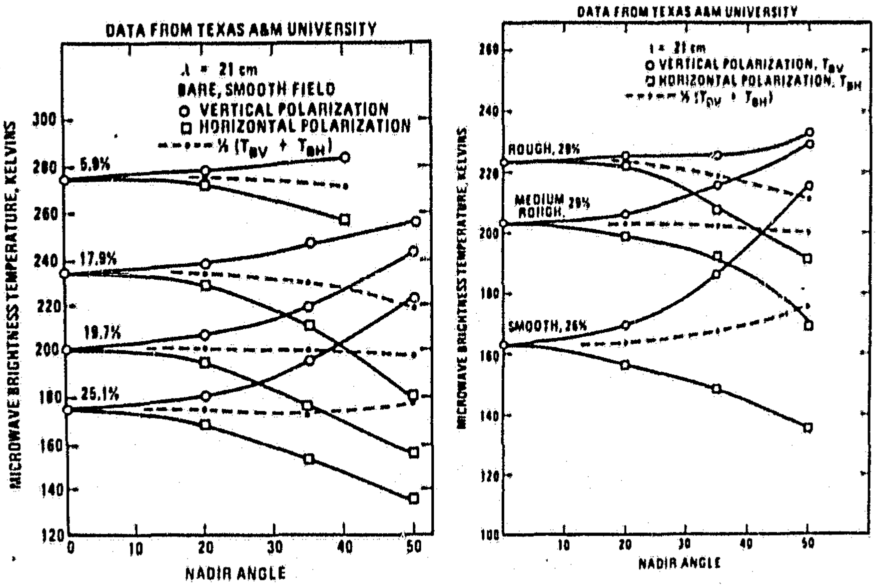

Figure 10. Results from Field Measurements Performed at Texas A&M University: (a) T_B versus angle for different moisture levels; (b) T_B versus angle for different surface roughness at about the same moisture level (Newton, 1976).

relationship of brightness temperature to soil moisture have been achieved using groundbased measurements acquired during controlled experiments. However, demonstration of the potential of passive microwave sensors for estimating soil moisture on an operational basis must be performed with aircraft and spacecraft sensors that integrate large areas of natural, nonidealized terrain. A series of aircraft experiments performed over the last several years by a number of investigators demonstrates the sensitivity of microwave radiometers to soil moisture in agricultural terrain. Skylab and Nimbus satellites have also provided significant results for very large areas of integration.

Aircraft experiments were flown over Phoenix, Arizona in February 1973 and March 1975. The agreement in bare field data for both years indicates that the results are repeatable. The results from the vegetated fields for the two years gives a curve whose slope is in good agreement with those for the bare fields. Thus, sensitivity to soil moisture is maintained through moderate vegetative canopies (alfalfa or wheat, with wheat being 20-30 cm high in 1973 and 50-60 cm high for the 1975 data).

Sensor results from five flights over a Hand County South Dakota test site in 1976 and 1977 were compared to the Phoenix results. The agreement is very good. These data were for a range of surface conditions including fallow fields, wheat, alfalfa and pasture.

Studies using the 21 cm data obtained by the S-194 instrument on board Skylab have shown significant correlations with soil moisture variations. The latter were determined either by moisture budget models (Eagleman and Lin, 1976) or by using the antecedent precipitation index (McFarland, 1976). This was a limited data set and its interpretation was hampered by the coarse spatial resolution (~ 115 km) of the sensor. However, the results are encouraging for the potential use of a sensor operating at this wavelength for soil moisture sensing. Improved spatial resolution can be obtained by using larger antennas. The antenna on the Skylab instrument was 1 m square. In the future it should be possible to deploy much larger antennas from the space shuttle and, for example, a 20 m antenna would yield resolutions in the 10 km range.

Active Microwave Response to Soil Moisture

a. physical basis

Analogous to the optical reflectivity of terrain, the backscattering coefficient, σ°, describes the scattering properties of terrain in the direction of the illuminating source. The scattering behavior of terrain is governed by the geometrical and dielectric properties of the surface (or volume) relative to the same properties (wavelength, polarization, and angle of incidence) of the incident illumination. Recall that the dielectric constant of a soil-water mixture is strongly dependent on its water content. Thus, in general, σ° of terrain is dependent on the soil moisture content of an effective surface layer whose thick-

ness is governed by the penetration properties of the terrain at the wavelength used; this thickness will be approximately the same for active and passive microwave approaches. In addition to its dependence on soil moisture content, however, $\sigma°$ is also in general a function of the surface (or volume) roughness and vegetation or snow cover (if not bare).

From an operational system standpoint, radar possesses two key capabilities of major importance to remote sensing applications, namely, a) its ability to make timely observations unhampered by cloud cover or time of day, which may be a very critical factor in hydrologic modeling, and b) its ability to generate high resolution imagery from space platforms. These system capabilities and the dependence of the soil dielectric constant on its moisture content indicate a high potential for soil moisture sensing with radar.

b. ground-based results

Over the past six years, the radar response to soil moisture content was extensively investigated by the University of Kansas, using a truck-mounted active microwave system (Ulaby, 1974; Ulaby et al., 1974 and 1975; Batlivala and Ulaby, 1977). The sensitivity to soil moisture content and the accuracy and precision with which it can be estimated were evaluated for both bare and vegetated fields.

b-1. bare ground

The objective of the bare field experiments was to determine the optimum radar parameters for minimizing the response to surface roughness while retaining strong sensitivity to moisture content. By examining the radar response to soil moisture of several fields with considerably different surface roughness conditions ranging from very smooth (dragged) to very rough (disced), the following set of optimum parameters was determined: $\lambda = 6\text{-}7$ cm, $\theta = 7° - 17°$ from nadir, and horizontal transmit-horizontal receive polarization (Ulaby and Batlivala, 1976). Figure 11 shows the response in this range of sensor parameters. Included are data for all fields, regardless of surface roughness. Also shown on the figure are the calculated error ranges corresponding to ± 1 standard deviation associated with the measurement of $\sigma°$ and the in situ measurement of m_1, the moisture content in the top 1 cm of the soil. A statistical analysis of these variances indicates that at these optimum parameters, the error (due to surface roughness) associated with the soil moisture estimate provided by such a radar system is comparable to the error associated with the in situ measurements of m_1 (Ulaby and Dobson, 1977).

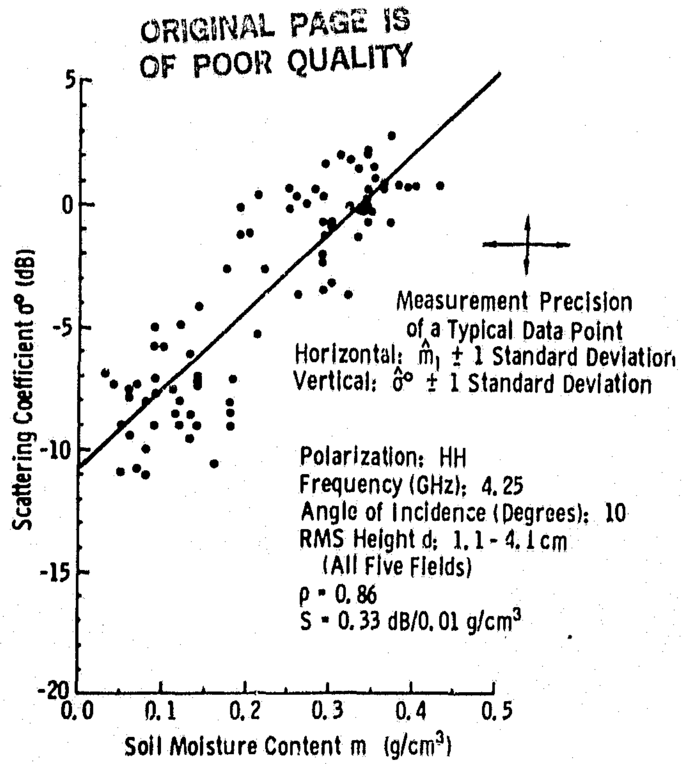

Figure 11. Scattering Coefficient as a Function of Moisture Content in Top 1 cm for 84 Data Sets (data from all five fields were included).

b-2. vegetation-covered ground

The presence of a vegetation canopy over the soil surface reduces the sensitivity of the radar backscatter to soil moisture by a) attenuating the signal as it travels through the canopy down to the soil and back, and by b) contributing a backscatter component of its own. Moreover, both factors are in general a function of several canopy parameters including plant shape, height and moisture content, and vegetation density.

c. aircraft and spacecraft results

Although no detailed airborne investigations have yet been reported on the active microwave response to the soil moisture content underneath a vegetation canopy, observations have been made with radar of the difference between dry soil and soil undergoing irrigation. For each of these fields, the effect of the irrigation on the radar return appeared to produce a difference of about 7 db at angles within 40° from nadir. Since all ground conditions, except for soil-water content, were similar over the entire field, the differences in σ° can only be attributed to the effect of moisture.

SATELLITE-BASED EXPERIMENTS

Remote sensing of soil moisture from space will be the logical follow-on to a research program which so far has included ground and aircraft experiments as well as modeling. Current soil moisture models employ a lumped parameter approach and are based primarily on point measurements distributed over agricultural fields, watersheds, or other areas of interest. Spacecraft systems, in contrast, will generally provide measurements of soil moisture integrated over the area covered by each sensor's footprint, i.e., from one to many square kilometers. Thus, remote sensing from space will by necessity give rise to new distributed parameter models based on large-area measurements. In fact, one of the major future research tasks will be to reconcile the results provided by these two measurement concepts, i.e., point-by-point or field average, and integrated large area coverage.

Thus, remote sensing from space will by necessity give rise to new distributed parameter models based on large-area measurements. In fact, one of the major future research tasks will be to reconcile the results provided by these two measurement concepts, i.e., point-by-point or field average, and integrated large area coverage.

There are many reasons why a research-oriented satellite system to provide remote sensing of soil moisture from space should be implemented in the near future:

1. To account for differences in soil texture, soil management and vegetation cover between different agronomic regions of the world, it is necessary to conduct investigations in several different climatic regions. Using aircraft, it would take many years before soil moisture algorithms usable over a wide range of climatic regions could be developed. Only satellites can effectively cover areas large enough to reliably provide synoptic data of whole regions in a repeatable and predictable pattern. This allows study of long-time series soil moisture estimation. Also, satellites provide the payload capability to carry an active/passive multispectral sensor complement, allowing for the possibility to acquire optimized data sets for each application.

2. Resolution, area size, area variability, and soil roughness and vegetation effects which are needed to develop models capable of using remote sensing input data from space cannot be adequately simulated on the ground. Thus the acquisition of time-sequential observations at a regular interval is the key to the extraction of useful soil water-related information from remotely sensed data. Such observations can be obtained reliably only from (in practice) ground-based or spaceborne platforms. Ground-based platforms can be used to test the information content that can be extracted from time-sequential observations for space-specific areas and surface conditions. Experience from airborne remote sensing missions has shown that the acquisition of similar data for extended areas using airborne platforms is very difficult, and the acquisition of sufficient data takes many years. This difficulty with airborne investigations is attributed to a combination of (a) aircraft scheduling and availability, (b) sensor performance, (c) stability of aircraft platforms, and (d) inability to fly exactly the same flightline each time. This last item is extremely important. Existing algorithms used for extracting soil moisture information from microwave data do not account for surface slope, since such information is not readily available. Hence, in nonflat terrain, we have to rely on the change in the microwave response between successive flights as the parameter to use for extracting soil moisture information. In this case, differences in flight directions and illuminated paths would introduce errors into the soil moisture estimation algorithm. The superior stability of the satellite platform, the repeatability of the sensor look-direction, and the dependable revisit interval, all add to the conclusion that an experimental satellite-borne microwave sensor package would be extremely desirable for soil moisture remote sensing.

3. Available data for active microwave remote sensing of soil moisture content indicate that the performance of a radar soil-moisture sensor is optimum if the radar look-direction is in the 7°-20° angular range relative to nadir. For this range of angles, the corresponding swath width on the ground is only 2.4 miles from a high-altitude aircraft altitude of 10 miles. Navigating at this altitude in a way that the test site of interest is actually illuminated by the radar is not an easy task. Since soil moisture is a dynamic variable, it is not possible to process the imagery and then retrospectively acquire the "ground-truth" information. In contrast, a soil moisture radar flown at an altitude of 600 km, provides an adequate swath width of 145 km.

Several satellite systems launched in the past have carried sensors capable of providing some data

useful to soil moisture research. They have included programs such as Nimbus, Landsat, Seasat-A, TIROS, and the Heat Capacity Mapping Mission (HCMM). While these missions provided visible, thermal IR, and active/ passive microwave measurements in various combinations, none of them was optimized for soil moisture, and no single satellite has had a full complement of sensors capable of fulfilling soil moisture requirements. In particular, no satellite previously flown or currently approved has the capability of providing passive microwave measurements in L-, S-, or C-bands, with the minimum acceptable resolution (10 km or better).

Similarly, no space system currently under study specifically addresses soil moisture requirements, although some of them may be developing sensors with potential usefulness to fulfill such requirements. In particular, technology to be developed for an Earth Resources Synthetic Aperture Radar (ERSAR) mission to be launched in the late 80's may prove useful for active microwave soil moisture measurements.

A two-phased approach appears to be a reasonable way to provide adequate remotely sensed soil moisture data from space. An initial satellite (Phase I) would be launched to provide a consistent and reliable data set for researchers, to enable them to work with adequate space data for the first time, and to allow them to develop models and other research methods to make use of such data.

Table 4a, 4b and 4c provide the current best estimates of requirements for agriculture, climate and hydrology for such a first system.

A second satellite (Phase II) would be launched several years after the first one. Requirements for this satellite would be based on the results of the Phase I mission, and its sensors would make use of state-of-the-art technology then available.

Because the satellite and its sensors are only one part of the overall system, their implementation must be preceded by a research program leading to the development of algorithms and other methods capable of utilizing the space data as soon as they become available. Similarly, and most importantly, a data processing facility must be developed as part of the space system, capable of providing processed data in timely fashion and in formats needed by researchers and other data users.

The following section provides details of various possible approaches to the Phase I and Phase II space systems.

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Table 4a
Phase I Space System (Mid to Late 1980's)
Preliminary System Requirements - Agriculture

SENSOR	SPECTRAL BANDS		SPATIAL RESOLUTION		TEMPORAL RESOLUTION		NEΔT OR NEΔP	COMMENTS
	DESIRED	ACCEPTABLE	DESIRED	ACCEPTABLE	DESIRED	ACCEPTABLE		
VISIBLE	0.4-0.5 0.5-0.6		<100 m		1-3 days			
THERMAL IR	8-12μ		<1 km		1-3 days		0.5°K	
PASSIVE μ WAVE	L, C (H and V)		<10 km		1-3 days		±1°K	
ACTIVE μ WAVE	L, C (Cross:HV)		<1 km		1-3 days		0.5 DB	

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Table 4b
Phase I Space System (Mid to Late 1980's)
Preliminary System Requirements - Climate

SENSOR	SPECTRAL BANDS		SPATIAL RESOLUTION		TEMPORAL RESOLUTION		NEΔT OR NEΔρ	COMMENTS
	DESIRED	ACCEPTABLE	DESIRED	ACCEPTABLE	DESIRED	ACCEPTABLE		
VISIBLE			100-200 km		3-6 days			
THERMAL IR			100-200 km		3 6 days			
PASSIVE μ WAVE			100-200 km		3-6 days			
ACTIVE μ WAVE			100-200 km		3-6 days			

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Table 4c
Phase I Space System (Mid to Late 1980's)
Preliminary System Requirements - Hydrology

SENSOR	SPECTRAL BANDS		SPATIAL RESOLUTION		TEMPORAL RESOLUTION		NEΔT OR NE$\Delta\rho$	COMMENTS
	DESIRED	ACCEPTABLE	DESIRED	ACCEPTABLE	DESIRED	ACCEPTABLE		
VISIBLE/NIR	μ .5-.6 .6-.7 .7-.8 .8-1.1	μ .6-.7 .8-1.1	50 m	50 m	1/day	3 days		
THERMAL IR	μ 10.5-11.5 11.5-12.5	μ 10.5-11.5 11.5-12.5	100 m	200 m	2/day	3 days	0.2°K	
PASSIVE μ WAVE	L, C (H and V)	L	10 km	25 km	1/day	3 days	0.5°K	
ACTIVE μ WAVE	C (H and V)	TBD	1 km	5 km	2 days	3 days	$\pm$0.5 DB	

FUTURE PROGRAM

MODEL-RELATED RESEARCH

If remote sensing is to be of any value in the measurement of soil moisture, several model-related problems need to be resolved. The procedures and models employed by user groups must be understood. These models will define the types of measurements that must be provided. The research program should first try to satisfy the current needs of the user group models. Following this, investigations should be conducted to determine how these models might be adapted to better utilize remotely sensed measurements. Finally, and perhaps most importantly, we should devote effort to the development of new models particularly suited to using the soil moisture remote sensing capabilities.

As a first step, it is suggested that a series of investigations be conducted to quantify the sensitivity of decision variables to the soil moisture components of the application models. Individual studies dealing with agricultural management, hydrologic forecasting and climate simulation should be conducted separately. Through such an investigation, the scientists involved with the data collection could become more involved with the user groups, their models and their problems.

In conjunction with the sensitivity studies described above, simulation studies should be conducted to evaluate the impact of various types of remotely sensed soil moisture data on model outputs and decision variables. Existing long-term ground-based soil moisture data sets could be used as surrogates for the type of data obtainable using remote sensing techniques. Model simulations would then be conducted to determine the model's performance with and without the ancillary soil moisture measurements. In these studies it will be necessary to select tests that have definite performance measures. In hydrology this might be how well the model simulates observed streamflows.

One of the most important research topics being studied in all application areas that utilize models is the development of relationships between point measurements and representative values for spatial units. This same problem is important in the remote sensing of soil moisture since it is not only critical to understanding the remotely sensed measurements-ground data relationship but also because it could provide a great deal of support for the use of remote sensing. The program should support and cooperate with those working in these areas.

Available remote sensing technology can at best provide an estimate of soil moisture within the surface layer of the soil (possibly to a depth of 5 cm). Most potential applications for soil moisture data require estimates through the root zone of the soil which can be a meter or more in depth. Schemes for extrapolating the surface measurements must be devised and tested. This research must remain closely aligned with current research related to soil-water movement and evapotranspiration. The models and schemes should be developed with the intent of applying them on a large area basis.

This type of research will not be conducted unless it is initiated and sponsored by remote sensing programs, because it is only useful if remote sensing methods are employed. Therefore, the soil moisture remote sensing program should attempt to involve soil and plant scientists working in these areas in the program.

Reliable relationships need to be developed between soil moisture, depth of measurement, areal distribution of moisture and remotely sensed data. These relationships should include as wide a range of conditions as possible in their calibration. Since it is impractical to test every possible situation, the data base should be expanded through the use of research simulation models. This will require further studies related to the development, calibration and verification of these models. Data collection programs and validation schemes should consider the needs of these models. In addition the use and development of these models should help to reduce the current empiricism.

Research in the areas of the thermal infrared and passive microwave remote sensing has yielded reliable electromagnetic interaction models. These efforts should be continued with an increased emphasis on incorporating the vegetative canopy in the model. Also, if these models are to be used for their intended application, the extension of limited data sets, it will be necessary to perform additional verification experiments. Laboratory measurements of electrical properties of materials should be conducted to strengthen the current data base.

Modeling active microwave interactions has not received sufficient attention even though an excellent body of theory exists. Two different approaches could be undertaken, one utilizing physical optics and the other small perturbations. A great deal of data already exists for the verification of these models.

Since all of these models were developed for columns with homogeneous layers, there is a need for evaluating their validity when used to represent spatial units. These analyses may indicate problems similar to those encountered in soil water modeling. This type of modeling work will be essential to the evaluation of spaceborne sensors with very large ground resolution elements.

An effort should be made to assemble into a single model the electromagnetic energy-matter-sensor interaction models used for the different spectral regions. In this form, it would be easier to compare the relative advantages of different systems for different problems.

Knowledge of the dependence of soil dielectric constant on its moisture content and textural composition is essential to theoretical model developments of active and passive microwave interaction with and propagation through soil media. Although the general behavior of the dielectric constant of soil is known, no models, empirical or theoretical, exist that account for the variation with soil texture. It is therefore proposed that an investigation be conducted to determine the dependence of the soil dielectric constant on soil texture.

Ground, aircraft and spacecraft data collection programs should consider the data needs of the user application models. Most of these projects are geared toward agricultural management and consider only the climatological variables, vegetation and soil moisture. Hydrologic investigations require the water balance for a well-defined watershed unit. Thus data need to be collected over not just agricultural fields but watersheds also. Data collection programs should consider this in design. The current data base for hydrologic studies is inadequate.

FUTURE GROUND-BASED STUDIES

Ground-Truth Data Acquisition

Although several remote sensing soil moisture experiments have been performed from ground-based, airborne and spaceborne platforms, it is often difficult to perform a quantitative comparison of the different experiments because of the differences in the ground-truth data acquisition approaches, procedures, accuracies, and precision. Hence, it is imperative that a manual defining a standard set of procedures and techniques be generated for the acquisition of ground-truth parameters. Such a manual should consist of sections pertaining to ground-based experiments, airborne experiments and spaceborne experiments. It should include spatial sampling frequency (in all three directions), temporal sampling frequency and measurement procedures of each significant parameter in the soil medium, the overlying vegetation or snow cover, if present, and pertinent environmental parameters. Table 5 provides a sample list of the key parameters of interest, along with typical sampling frequencies usually used in conjunction with ground-based experiments conducted by various university researchers.

Table 5

Significant Target Parameters for a Soil Moisture Estimation Program

Parameter	Time Sampling Interval	Depth Profile from Soil Surface
A. Soil		
1. Soil Moisture (% by dry weight of soil)	concurrent with sensor observation	0-1, 1-2, 2-5, 5-9, 9-15, 15-45, 45-75, 75-105 cm.
2. Soil Temperature and phase of H_2O (ice, liquid)	concurrent with sensor and continuous	
3. Soil Resistivity		
4. Soil Bulk Density (g/cm^3)	not necessarily concurrent	Deeper depths not required for each sample data. This is needed to develop profile water budget models.
5. Soil Texture (% Sand, Silt, Clay) by horizons		
6. Soil Organic Matter Content (% of weight)		
7. Soil Salinity		
B. Soil Surface Configuration		
1. Regional Surface Slope (%)		surface only
2. RMS Surface Roughness (cm) parallel and perpendicular to sensor orientation		
a) Ridge/furrow characteristics and orientation		
b) Microrelief of soil aggregates (clods and peds)		
C. Soil Cover		
1. Vegetation Cover		not applicable
a) Type and height		
b) LAI		
c) Density (N/M^2 or g/M^2)		
d) Row orientation and spacing		
e) Ontogenetic stage		
f) Plant moisture (% of wet weight)	concurrent with sensor observation	
2. Snow Cover		profile as determined by snow stratification
a) Snow stratification		
1. snow density (g/cm^3)		
2. snow crystalline structure		
b) Snow wetness (% liquid H_2O by weight or volume)		
c) Snow depth (cm)		
d) Total water equivalent (cm)		
e) Snow temperature	concurrent with sensor observation and continuous	5,10,15,20,...cm
D. Meteorological Conditions		not applicable
1. Temperature		
a) Surface temperature		
b) Air temperature		
2. Barometric Pressure		
3. Relative Humidity		
4. Incident Solar Radiation		
5. Precipitation		
6. Wind		
a) Speed		
b) Direction		

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In generating the above manual, the following list of sources and/or background information should be incorporated (among others):

(a) USDA standard procedures if applicable, such as for soil textural analysis.

(b) Statistical analyses of the temporal variability of soil moisture.

(c) Statistical analyses of the spatial variability of soil moisture.

(d) Ground truth manuals generated in conjunction with previous investigations, such as the NASA/JSC Ground Truth Plan for 1978 Colby, Kansas Experiment.

Ground-Based Remote Sensing Experiments

It is most likely that future operational remote sensing soil moisture systems will consist of optical, thermal IR, active microwave (AMW) and passive microwave (PMW) sensors. To date, most experiments have utilized only one of the four systems. A few have used two systems, for example, optical and thermal IR, thermal IR and PMW, PMW and AMW; however, the two systems were merely compared with little or no effort devoted to integrating the systems into a complementary unit. What is urgently needed is a comprehensive experiment in which the four systems are mounted on the same platform (both trucks and aircraft) in such a manner that all sensors will "see" the same fields at the same time. The experimental sites should be carefully selected to represent different climates, different soils, various crops, and a variety of soil water profiles. Experiments of this nature would provide the necessary data from which the relative strengths and weaknesses of the various systems could be precisely evaluated and the strengths of each integrated into a composite system for estimating soil moisture.

Prior to or concomitant with the above, experiments are needed to develop algorithms to estimate soil moisture for particular sensors and/or combination of sensors for various target conditions. The following proposals stress research with microwave sensors, although many of the problems are pertinent to the thermal IR. It would be relatively easy to add thermal IR measurements.

Objectives

In addition to soil moisture content, the sensor response is, in general, influenced by other soil parameters, such as surface roughness and soil type, and cover parameters, such as vegetation density, plant water content, canopy temperature, etc. The objectives of ground-based experiments (with truck-mounted or tower-mounted sensors) are:

(a) Establish a selected set of resolutions required for both field sampling and large area sampling, i.e., 1-10 acres, 10-20 km and 100-200 km

(b) Establish the dependence of the sensor response on individual as well as combinations of target parameters, while keeping the others approximately constant

(c) Establish the target-sensor interaction process at several potentially-applicable combinations of sensor parameters (frequencies, angles of incidence and polarization configurations) and combinations of sensors (AMW, PMW, TIR and visible), so that optimum soil moisture estimation algorithms can be generated

(d) The results of (c) above can serve to define specifications of airborne and spaceborne sensors and to guide in the planning of airborne and spaceborne experiments.

Approach

The ground-based research program should incorporate each of the following links:

(a) In addition to establishing the soil moisture prediction capabilities of AMW, PMW, TIR and visible sensors separately, the additional incremental improvement provided by the combined use of these sensors should also be established. To date, two such experiments have been conducted through joint efforts by the University of Kansas and Texas A&M University (1974 at TAMU's Agricultural Research Farms, and 1978 at the Colby, Kansas site). To facilitate and increase the number of such multisensor experiments in the future, it is proposed that active microwave sensors be added to platforms carrying passive microwave (and TIR) sensors and vice versa.

(b) Whereas ground-based investigations can provide continuous records (temporally and in terms of sensor parameters) of specific sites, airborne investigations can provide temporally discrete records of the spatial variability over a given area. Through the implementation of combined ground-based and airborne investigations, the spatial-temporal link can be better established.

(c) Because ground-based investigations are site-specific, multiple experiments should be conducted in different climatic regions.

(d) Some ground-based investigations involve the acquisition of detailed temporal and spatial information about soil parameters. These investigations should be linked to the soil moisture profile model development activities, particularly during the early stages of these activities.

Target Parameters

Microwave scattering and emission from area-extended targets are characterized by the scattering coefficient, σ^o, and brightness temperature, T_B, respectively. Research to date indicates that the key factors influencing σ^o and T_B are:

a) Soil moisture profile

b) Soil temperature profile (influences T_B only)

c) Soil bulk density profile

d) Soil texture profile (soil type)

e) Soil surface and volume geometry (microroughness and macroroughness)

f) Cover type (vegetation and/or snow) and condition

g) Others (surface slope, general topography, etc.).

Proposed Investigations

Figure 12 is an idealized flow chart depicting the natural progression one might adopt in the development of soil moisture estimation algorithms using a remote sensing system. The flow chart is applicable to passive as well as active microwave sensors. In practice, however, the various soil parameters cannot be completely separated, and hence several iterations and combinations of the experiments outlined in the flow chart should be conducted. Coupling the basic approach shown by the chart with the results of investigations conducted to-date, Tables 6a through 6f have been prepared to outline specific investigations that should be conducted over the next few years in order to meet the objectives previously stated, in concert with the approach described.

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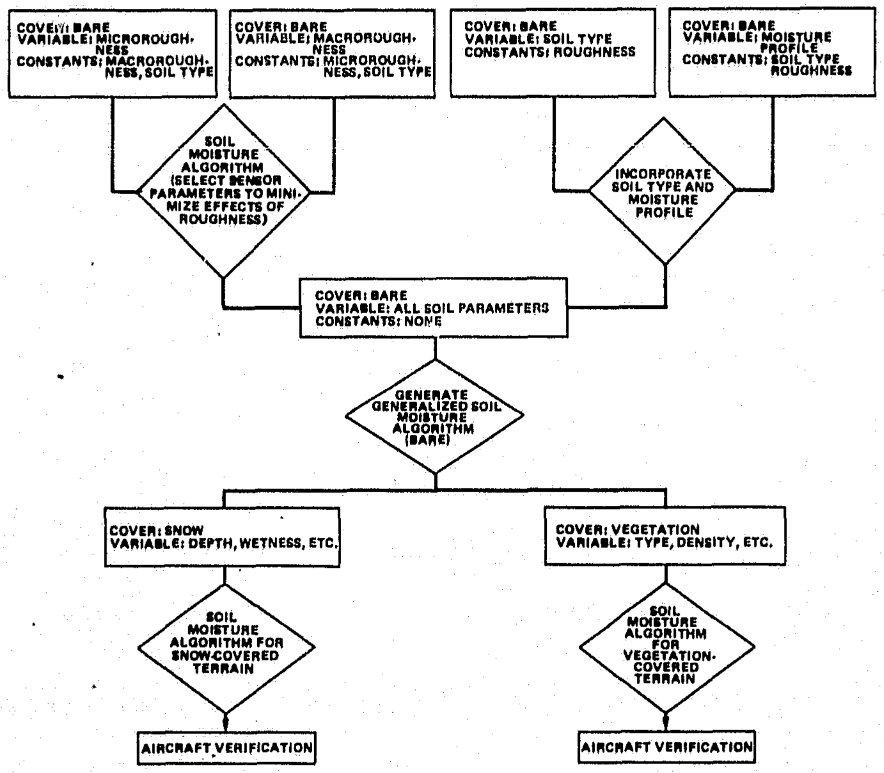

Figure 12. Flow Chart for Ground-Based Soil Moisture Investigations.

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Table 6a
Soil Surface Roughness

INVESTIGATION TITLE: Determination of the Effects of Soil Surface Roughness (Macro and Micro) on the Microwave Response to Soil Moisture of Bare Fields

PURPOSE: To evaluate the active and passive microwave response to:

a) Small scale surface roughness (micro)
b) Large scale surface roughness (macro), such as irrigation, patterns, row crops, etc.

OBJECTIVE: To choose sensor parameters (or combinations of sensor parameters) such that the dependence on surface roughness is minimized while maintaining sensitivity to soil moisture

PLATFORM: Truck-Mounted Boom

MW SENSOR	POSSIBLE SITES	FY	AVAILABLE SYSTEMS
PASSIVE	Texas Beltsville, MD Santa Barbara County, CA	1979-80 ? ?	TAMU's MSAS GSFC Truck JPL Truck
ACTIVE	Kansas	Micro--compl. Macro--79-80	Univ. of Kansas' 1-8 GHz MAS
PASSIVE/ACTIVE	TBD	1980-81	TBD

TIR should be included in all experiments

Table 6b
Soil Texture (Type)

INVESTIGATION TITLE: Determination of the Effects of Soil Texture on the Microwave Response to Soil Moisture of Bare Fields

PURPOSE: To evaluate the sensitivity of the active and passive microwave soil moisture response to soil type

OBJECTIVE: To determine a soil moisture descriptor (such as % field capacity) which incorporates soil texture through:

a) Dielectric measurements of different soil types
b) Scattering and emission measurements of different soil types

I. DIELECTRIC MEASUREMENTS

Data: Real and Imaginary parts as a function of moisture content
Frequencies: 0.5, 1.0, 1.5, 3, 5, 8, 10 GHz
Soil Types: 5 types between sand and clay

II. SCATTERING AND EMISSION MEASUREMENTS (Truck-Mounted Platform)

MW SENSOR	POSSIBLE SITES	FY	AVAILABLE SYSTEMS
PASSIVE	Texas Beltsville, MD Santa Barbara County, CA	1980-81 ? ?	TAMU's MSAS GSFC Truck JPL Truck
ACTIVE	Kansas	1978-80	Univ. of Kansas' 1-8 GHz MAS
PASSIVE/ACTIVE	TBD	1980-81	TBD

TIR should be included in all experiments

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Table 6c
Soil Moisture Profile

INVESTIGATION TITLE: Effects of Soil Profile Layering and Soil-Water Profile Changes of Bare Fields

PURPOSE: To evaluate thermal IR, active and passive microwave response to:

a) Coarse/fine and fine/coarse texture layers--uniform water content
b) Uniform soil--wet soil over dry and dry over wet
c) Layered soil--wet soil over dry and dry over wet
d) Nonuniform soil--nonuniform water

OBJECTIVE: Since remotely estimated soil moisture content is to provide the boundary conditions for soil moisture profile models, the "effective" depth responsible for the observed sensor output should be established. Through experiments of the type described above, it may be possible to define a depth transfer function which can be used with multifrequency systems to estimate the soil moisture profile shape in the top 1-15 cm.

PLATFORM: Truck-Mounted Boom

MW SENSOR	POSSIBLE SITES	FY	AVAILABLE SYSTEMS
PASSIVE	Texas Beltsville, MD Santa Barbara County, CA	1980-81 ? 1979-?	TAMU's MSAS GSFC Truck JPL Truck
ACTIVE	Kansas	1980-81	Univ. of Kansas, 1-8 GHz MAS
PASSIVE/ACTIVE	TBD	1980-81	TBD

TIR should be included in all experiments

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Table 6d
Vegetation Cover

INVESTIGATION TITLE: Determination of the Effects of Vegetation Cover

PURPOSE: To evaluate the effects of vegetation cover on the active and passive microwave response to soil moisture as a function of:

a) Vegetation parameters (type, density, height, H_2O content, etc.)
b) Sensor parameters (frequency, angle, polarization)

OBJECTIVE: To either:

a) Choose sensor parameters such that the vegetation cover has neglible effect on the accuracy of the soil moisture estimate,
OR,
b) If a) is not possible, generate a corrective factor to account for the effects of the vegetation cover

PLATFORM: Truck-Mounted Boom

MW SENSOR	POSSIBLE SITES	FY	AVAILABLE SYSTEMS
PASSIVE	Texas Beltsville, MD Santa Barbara County, CA	1979-80 ? ?	TAMU's MSAS GSFC Truck JPL Truck
ACTIVE	Kansas	1979-80	Univ. of Kansas' 1-8 GHz MAS
PASSIVE/ACTIVE	TBD	1981-82	TBD

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Table 6e
Snow Cover

INVESTIGATION TITLE: Determination of the Effects of Snow Cover

PURPOSE: To evaluate the effects of snow cover on the active and passive microwave and TIR response to soil moisture

OBJECTIVE: To either:

a) Choose sensor parameters such that the snow cover has negligible effect on the accuracy of the soil moisture content estimate, OR,
b) If a) is not possible, generate a correction factor to account for the effects of the snow cover
c) Estimate snow depth on agricultural lands as a by-product of a) and b) above

PLATFORM: Truck-Mounted Boom

MW SENSOR	POSSIBLE SITES	FY	AVAILABLE SYSTEMS
PASSIVE	TBD Minnesota TBD	1980-81 ? ?	TAMU's MSAS GSFC Truck JPL Truck
ACTIVE	Kansas	1980-81	Univ. of Kansas' 1-8 GHz MAS
PASSIVE/ACTIVE	TBD	TBD	TBD

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Table 6f
Diurnal Variations

INVESTIGATION TITLE: Determine the Significance of the Rate of Change of Soil Moisture Relative to Its Absolute Value on the Microwave and TIR Response

PURPOSE: Since the response of passive microwave and TIR sensors depend on the moisture content profile as well as the physical temperature profile, evaluate the dependence of the emitted radiation of the rate of change of temperature and soil moisture content

OBJECTIVE: The results of this investigation can provide information pertinent to:

a) Choice of time of day for overpass of an area
b) Potential use of rapid temperature changes (sunrise) in estimating soil moisture

MW SENSOR	POSSIBLE SITES	FY	AVAILABLE SYSTEMS
PASSIVE	?	1980-82	TAMU's MSAS
	?	?	GSFC Truck
	?	?	JPL Truck

Additional Systems

For conducting ground-based backscatter and emission experiments, we are currently limited to three passive microwave systems and one active microwave system. In lieu of developing additional systems, we propose that each of the above four systems be converted to passive/active microwave, IR and possibly visible and near IR systems by:

a) Adding scatterometers at selected frequencies to the radiometer platforms

b) Adding radiometers at selected frequencies to the MAS system

c) Adding TIR radiometers to all systems.

Such a conversion will produce four systems at four geographically different locations. Any future systems developed for field measurements should be designed with the full complement of visible, thermal infrared, and active and passive microwave sensors.

Recommendations:

a. Whenever possible, electromagnetic soil-moisture measurement investigations should be conducted by teams that include sensor specialists as well as soil scientists. Effective interaction between sensor engineers/scientists and soil scientists/agronomists/hydrologists is essential to the successful development of useful soil moisture remote sensing techniques and algorithms.

b. The development of new in situ techniques for sampling soil moisture content is needed. USDA's plans to develop such techniques under the AgRISTARS project are endorsed by the Soil Moisture Working Group. However, it is important that the specifications be coordinated with the Soil Moisture Working Group.

c. Whenever feasible, test sites used for ground-based or airborne investigations of soil moisture should be selected to be on land areas that are part of ongoing state or federal water-related projects such as the Salt River Project in Arizona, the Wellton-Mohawk Irrigation and Drainage District Project also in Arizona, and the AgRISTARS Project Supersites in Iowa and South Dakota.

d. In addition to using soil moisture content as an indicator of soil water capacity, the capability of remote sensing devices to monitor other soil water attributes, such as water depletion (rate of change of water in the top 30 cm of the soil), should be investigated.

AIRCRAFT EXPERIMENTS

While ground-based systems offer the best experimental control, they are limited in movement and this restricts the range of environmental conditions that may be observed. Aircraft systems can carry the instruments over a much larger area during a relatively short time frame and, therefore, remove the spatial restriction which applies to a ground-based system.

The major functions of the aircraft program are to:

1. Extend the controlled data base beyond what is possible with ground-based systems

2. Provide testing and verification of application models

The first objective in development of any remote sensing application must be establishment of a well-controlled data base consisting of calibrated measurements spanning the full range of anticipated target and sensor parameter variations. These include:

Sensor Parameters	Target Parameters
1. Frequency	1. Moisture content and profile
2. Incidence angle	2. Soils
3. Aspect angle	3. Roughness
4. Polarization	4. Vegetation cover
5. Resolution	5. Temperature - surface and profile

These data are first used to verify theoretical models and to define their limitations. Correlation analysis of the experimental data permits extension of the models by incorporation of empirically defined relationships.

These physical (theoretical plus empirical) models of the interaction mechanism are then the basis for development of application models. In some cases this may be a direct empirical relationship between measured parameters and the desired output information. In other cases ancillary data and additional modeling may be required to transform the measured data to a form compatible with the desired application.

In any case, considering the range of possible data combinations represented by only the parameters listed, it is obvious that establishment of a comprehensive data base remains a formidable task. This is particularly evident for establishment of empirically based application models.

While ground-based systems offer the best experimental control, they are limited in movement, restricting the range of environmental conditions that may be observed. Aircraft systems easily overcome this spatial restriction; however, they are more severely constrained by temporal restrictions. While this temporal constraint is primarily due to sharing the aircraft with other sensors and applications, it has proved to be a major obstacle in extension of the data base.

Past experience with aircraft experiments has demonstrated that one of the principal difficulties is obtaining a range of moisture conditions during the time in which the aircraft is available. During the past five years, some six soil moisture aircraft experiments have been conducted spanning a reasonable range of moisture conditions. However, the bulk of this data has been acquired in the semi-arid high plains region with similar soil, vegetation and climatic regimes. While additional experiments in this region would still yield valuable additions to the data base, it seems that priority should first be given to extending the data

base to different climatic regimes. This will provide additional verification of theoretical models but more importantly will establish the generality of empirically derived relationships.

The following table of general soil moisture applications and climatic regimes points out the current status of the soil moisture data base.

Application	Climate		
	Arid	Semi-Arid	Humid
Water Resources	3	2	1
Agriculture	2	3	1
Climate	3	2	1

(1) Little or no data
(2) Limited data
(3) Extensive data

From the standpoint of both current data status and importance of the application on a regional or national scale, it is evident that attention should be given to humid regions. Accordingly, extension of the data base to humid climates for all applications is taken as the top priority for future aircraft experiments.

~~Extension of the controlled data base of soil~~ moisture measurements should not concentrate solely on increasing the observed range of target-sensor parameters. As models of the interaction mechanism for each candidate sensor become more developed, it becomes increasingly important that all sensors be evaluated for their complementary capability in a multisensor measurement role. This will require data sets of simultaneous measurements for each sensor along with supporting ground truth. Ground-based programs are currently devoted to single sensor investigations with considerable logistic problems involved in performing simultaneous measurements. The complement of sensors aboard the C-130 makes the aircraft program a logical choice for conduct of multisensor experiments. The groundbased systems should be converted to multisensor capability, as called for in the section on Future Ground-Based Studies, in order to more readily extend a complete controlled data base.

The second objective of the aircraft program, to provide testing and verification of application models, is in a sense even more complex than the first. This is due to the fact that very few applications require soil moisture in the depth interval or at the scale measured by microwave systems. Soil moisture in the upper layers may be simply one component affecting an empirical relationship or it may serve as an input to another model. Thus, the testing and verification process is not simply of the ability to measure soil moisture, but of the improvement in the application model due to the microwave soil moisture input. This presents a real problem in evaluation of applications models; in many cases a directly comparable model using soil moisture does not exist, since soil moisture information is not available as such from current sources. This problem is further compounded by the fact that most end-use applications models are extremely coarse in scale and are continuous in nature with the current state due to the previous history. Thus there is the question of how the data should be aggregated for comparison and how only an evaluation must be conducted for differences to be noticeable. Where the comparison is between an existing and a proposed model for a region, there is also the question of a criteria for determining which is best where differences are significant.

As an illustration of this difficulty, models of root zone soil moisture may be formed which have as input meteorological data alone and meteorological data supplemented with microwave data. The relative accuracy of these models can be checked on a point basis where the root zone moisture can be physically sampled. However, averaging to a larger region will undoubtedly affect the results of each model, and thus there is some question as to whether point testing is a sufficient performance criterion of even this parameter. To further complicate this, the actual application usually utilizes something like crop yield as the ultimate criterion. However, the interaction of the differing root zone soil moisture models in the yield equation may be far different. Thus, the best moisture predictor could conceivably not always give the best yield prediction if empirical relationships to meteorologic data are employed. In using yield as a criterion, there is additionally the problem that only one data point per season is available, requiring multiple regions to acquire sufficient data for evaluation.

This all points to the fact that evaluation and test of soil moisture measurement applications is not yet well defined. This is due to the lack of soil moisture data.

One additional consideration for the aircraft program should involve incorporation of radar image data in the experiment design. Although most of the radar applications presuppose resolution from satellites compatible only with synthetic aperture, the measurements program has been conducted almost exclusively with scatterometer instruments. The original rationale for scatterometer development was to produce an instrument capable of calibrating an imaging system. This step of providing absolute calibration of image data has not yet been addressed and should be investigated through the aircraft program.

The areas which both need investigation and which must involve aircraft experiments could be broken down as follows:

1. Data Base Extension
2. Effect of Spatial Averaging
3. User Applications Model Evaluation

For the first of these there is a readily apparent need to extend the data base to humid regions. For the other two areas there is a pressing need for aircraft data to address these questions; however, there is not yet sufficient information to design specific experiments. Accordingly the priority here must first be on experiment definition which must include user input and provide acceptable control and evaluation criteria.

In addressing these objectives, considerable attention should be devoted to improvement of the aircraft data processing capability. The time lag and cost of obtaining data after an experiment is currently excessive even for relatively small experiments. As the program moves to providing data for larger scale application testing and verification experiments, similar to that conducted at Colby, this processing bottleneck will become even more serious.

To illustrate this point, many of the proposed applications such as irrigation scheduling require extremely short turnaround of the data to be of any use at all. To evaluate eventual applications systems requiring one- or two-day turnaround of the data with a system requiring several months for data processing does not seem reasonable.

This task of experiment definition should attempt to utilize the existing data from the Colby mission where possible. The scale and duration of this data set should make possible some initial definition of the problems in defining experiments for applications model verification. This will require a substantial effort in continued reduction of the Colby data and in evaluation of it for this purpose.

Data Base Extension

1. In 1980, conduct only the aircraft experiments already scheduled. Where possible, such as with the Phoenix-Davis IR flights, the experiment should be expanded to include microwave measurements as well.

2. In 1981, conduct a humid region experiment using all available systems over a well-controlled site. In particular, the experiment should span some reasonable length of time. Six flights spaced at three day intervals are proposed. It is tentatively suggested that the test site be selected in the Mississippi delta.

3. In 1982, schedule a repeat of the 1981 humid area experiment. This is suggested due to previous experience in obtaining the full range of desired variations in a limited time frame. If the 1981 experiment does accomplish all objectives, this experiment may be relocated to another humid region or even perhaps to an arid region.

4. No specific flight experiments are proposed at this time beyond 1982, as it is felt this should await reduction and analysis of existing data sets and those proposed for 80-82.

Effect of Spatial Averaging

1. Efforts here should concentrate on defining user compatible resolutions and acceptable criteria against which remotely sensed averages may be compared. Where possible these should be fed into the experiment design of the humid area extension as an additional objective.

User Applications Model Evaluation

1. The user models appropriate for inclusion of remotely sensed data must be developed.

2. Experiment design must provide a comparison of models with and without remote sensing input or criteria to evaluate the incremental improvement added by the remotely sensed data.

SATELLITE SYSTEMS

The section on Satellite-Based Experiments discussed reasons why a first satellite system (Phase I) to monitor soil moisture should be implemented in the mid-eighties. A second more advanced system (Phase II) would be implemented a few years after the first one.

In essence, the Phase I system would provide researchers with consistent and reliable remote-sensing soil moisture data sets. Such sets would allow them to develop models making use of the large area integrated measurements possible from space, to optimize measurement parameter and system requirements, and finally to evaluate the merits of the sensor systems and their respective spectral bands provided by a Phase I payload.

A Phase I system could be launched as early as 1986 or 1987. Previous research, Schmugge, et al. (1979), has indicated that L-band passive radiometry and C-band active measurements yield usable data, but that a multispectral approach might improve results. Accordingly, it is desirable to consider several microwave sensor options for the implementation of a Phase I system, ranging from a simple single frequency, single polarization radiometer to a multifrequency, multipolarization active/passive sensor.

Phase I System

Three options should be considered for the Phase I space system (see Table 7). The simplest is Option 1A. It would carry a sensor similar to the Advanced Very High Resolution Radiometer (AVHRR) to provide thermal infrared and visible measurement data, and an L-band radiometer with a 10 m x 10 m phased array antenna, sufficient to provide a resolution of 5 to 10 km. Option 1B would add a C-band radar to these two sensors, using an additional array panel as its antenna. Option 2 is the most complex of the three. It would also carry an AVHRR, but the microwave sensor would consist of a mechanically scanning 15 m antenna which radiometer and radar sensors would time-share. The radiometer portion would be multichannel with L-, S-, and C-bands possible. The radar would be C-band and could be used for both precipitation and soil moisture studies.

A selection between these options must await a further definition of mission requirements, an analysis of how well the requirements can be met by each of the options, as well as tradeoffs between costs, risk and the state of the art of the large reflector technology required for Option 2. No technical innovations are required for implementation of Options 1A and 1B.

The spacecraft would be launched into an orbit sim-

Table 7
Phase I Soil Moisture Mission Options

Option	Visible/IR Sensor	Microwave Sensor
1A	AVHRR	10 x 10 m array Single Frequency (L-band) Single Polarization (hor)
1B	AVHRR	Same as Option 1A plus C-band radar with array antenna
2	AVHRR	15 meter dish Radiometer with multiple frequencies (L-, S-, C-bands) and multiple polarizations Radar (C-band) for soil moisture and precipitation measurements

ilar to the one flown by the Heat Capacity Mapping Mission (HCMM), i.e., a 600 km sun-synchronous orbit, with a 1:30 p.m. ascending mode equator crossing.

Phase II System

It is expected that research results from the first mission will permit the development of definitive mission requirements for Phase II, as well as an optimized definition of sensors and their parameters, i.e., spectral bands, spatial and temporal resolutions for both active and passive sensors, depression angles and polarizations.

Although it is premature to define the Phase II satellite, it is possible to speculate that it might carry a synthetic aperture radar to measure soil moisture with resolutions of 100 m or better. Improvements in large deployable reflector and phased array technology will significantly improve microwave radiometer resolution over what is possible today. It is likely that precipitation over land can be measured by a spaceborne radar, and that such a radar may be part of a Phase II system. Finally, because of expected advancement in the field of solid state sensors, thermal IR and visible observations will be made with higher resolutions and higher sensitivities than are possible with the Phase I system.

Correlative Ground Truth Measurements

The ability to collect large volumes of correlative data coincident with satellite passes obviously enhances the validity of any statistical analysis. Continued, repetitive, uniform data collection is basic to any real understanding of the natural phenomenon being studied. As an example of such data collection, NOAA/NESS has established a test site at Luverne, Minnesota, (Cornbelt), which now consists of an Idaho Instruments RSG 1/2 radiometric soil moisture automatic recording gauge. In addition, there are plans to extend this monitoring to include soil temperature, air temperature, solar insolation, and near-surface wind velocity. A working agreement with the Luverne Soil Conservation Service local office allows NOAA/NESS to secure gravimetric soil moisture values through the entire site area ($\sim$100 mi^2) when necessary.

The Luverne site is of twofold interest, because of its strategic position along the NWS/Office of Hydrology flightline for a gamma-ray aircraft survey, which is periodically flown "operationally" for snow-water-equivalent measurements and for soil moisture. The large ($\sim$1500 ft) footprint is useful for satellite sensor comparisons with HCMM or SMMR because it tends to integrate the minor fluctuations into a more meaningful areal measurement. It is believed that a series of gamma-ray flights would be appropriate over the Luverne test site and would assist in the evaluation of spaceborne sensor data for soil moisture determination.

It is expected that this instrumented test facility will provide the capability for extended seasonal and diurnal monitoring, and that it will be possible to compare the measurements obtained in this manner with those acquired by the SMMR, HCMM, The-

matic Mapper and other sensors now or soon to be in orbit. Similar ground data collection sites representing different climatic and geographic regions would be required as research areas for the proposed satellite system. The planning for such ground truth test sites should be an integral part of the space system definition and design.

Summary

The use of dedicated space-derived soil moisture data will only come about from a coordinated program of ground, truck, aircraft, and available spacecraft measurements and experiments. Ultimately, a Space-Based Moisture System is seen as a service, providing data on a multidisciplinary basis with a communication and data processing and distribution system decentralized to areas of interest (see Figure 13).

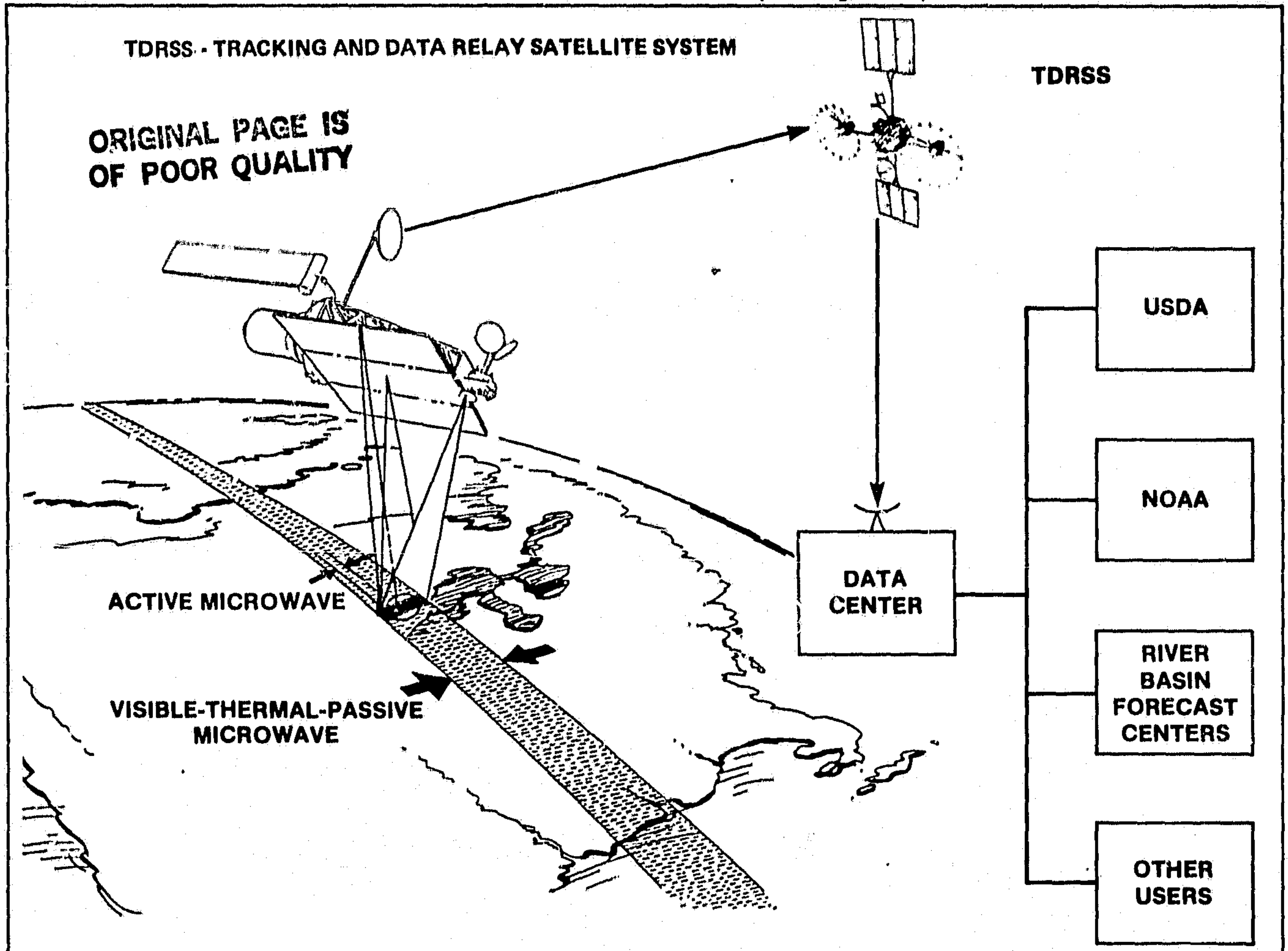

Figure 13. Soil Moisture Monitoring System.

PROPOSED EXPERIMENTS AND RESEARCH TASKS

Significant progress has been made in the development of remote sensing techniques for estimating soil moisture, and some useful applications for soil moisture information have been demonstrated. However, a research-oriented program is necessary to answer an array of questions before an operational program is appropriate. This research program is to develop the capability of estimating soil moisture from space.

Specific objectives of this program should be to:

- Define physical parameters involved and evaluate the interaction between electromagnetic energy, soil moisture and associated factors.
- Compare and evaluate measurement systems and techniques for measuring and estimating soil moisture.
- Begin consideration of data handling and distribution procedures adaptable to users in water resource management, agriculture, and climate.
- Establish a working group to coordinate the research and development program and obtain user input.
- Conduct periodic workshops to disseminate results.

To meet the objectives of the soil moisture program, the following five year (1979-1984) research and development plan is recommended:

- Conduct comprehensive controlled experiments at three to five locations in the U.S. under variable conditions of climate, soils, crops, topography, etc. Suggested locations include arid southwest/west, southern Great Plains, northern Great Plains, midwest, southeast. The research should include:
  - Multispectral (visible, IR, passive and active microwave) sensors
  - Study of sampling depth, vegetation effects, roughness effects, soil moisture profile dynamics, time rate of change effects, resolution requirements
  - Development and improvement of models
  - Test of transferability of models and algorithms between sites
  - Evaluation of phenomena related to soil moisture (precipitation, yield, crop-water stress, plant-water content, etc.)
- Conduct research at ground, aircraft, and spacecraft altitudes:
  - Utilize ground and truck-mounted sensors
  - Utilize contract aircraft making repeat visits to the sites
  - Utilize existing and planned NASA and NOAA orbital systems (Landsat-C and -D, Seasat, GOES, HCMM, Tiros-N, Shuttle, etc.)
- Conduct modeling and simulation studies for weather and climate:
  - Prepare global data sets of soil water, evapotranspiration, vegetation, and soils. Analyze existing spacecraft data sets, e.g., Nimbus 5 ESMR through Nimbus 7 SMMR, to provide climatic baseline information
  - Develop ground hydrology parameterizations for atmospheric general circulation models
  - Optimize the design of soil water observing systems by GCM simulation studies
  - Investigate the sensitivity of weather and climate to soil water and evapotranspiration
- Conduct pilot tests:
  - Irrigation scheduling (Table 8 shows irrigation pilot test details)
  - Runoff forecasting
  - Agricultural yield prediction
  - Weather and climate prediction
- NASA should initiate preliminary planning of a first generation soil moisture/water resources satellite:
  - Five to seven years may be required to put the satellite into operation
  - A single satellite oriented toward soil moisture and water resources will lead to more orderly research and development efforts
  - A single satellite will facilitate dissemination of data to users

Table 8
Pilot Test - Irrigation Scheduling

OBJECTIVE:	To develop operational use of remote sensing in the Water and Power Resources Service's Irrigation Management Services (IMS) to directly transfer scheduling information to farmers.
APPROACH:	Analyze thermal and microwave data from aircraft and spacecraft to determine utility of data as input to IMS program. Both crop and soil moisture are required.
EXPECTED RESULTS:	The effort should obtain quantitative models for predicting inputs into the IMS program. Recommendations will be made as to data timeliness required for an operational system of irrigation scheduling, and potential uses of present and future sensor systems.

In order to accomplish these objectives, specific research tasks must be completed as well as conducting some specific experiments that will be widely applicable to agriculture, hydrology, and climate. The research tasks have been delineated, as shown in Figure 14, according to major emphasis areas, namely, modeling, ground-based studies, aircraft experiments, spacecraft mission, user test programs and other tasks. Specific experiments which include effort in more than one of these major emphasis areas (listed in the schedule) are shown in Table 9.

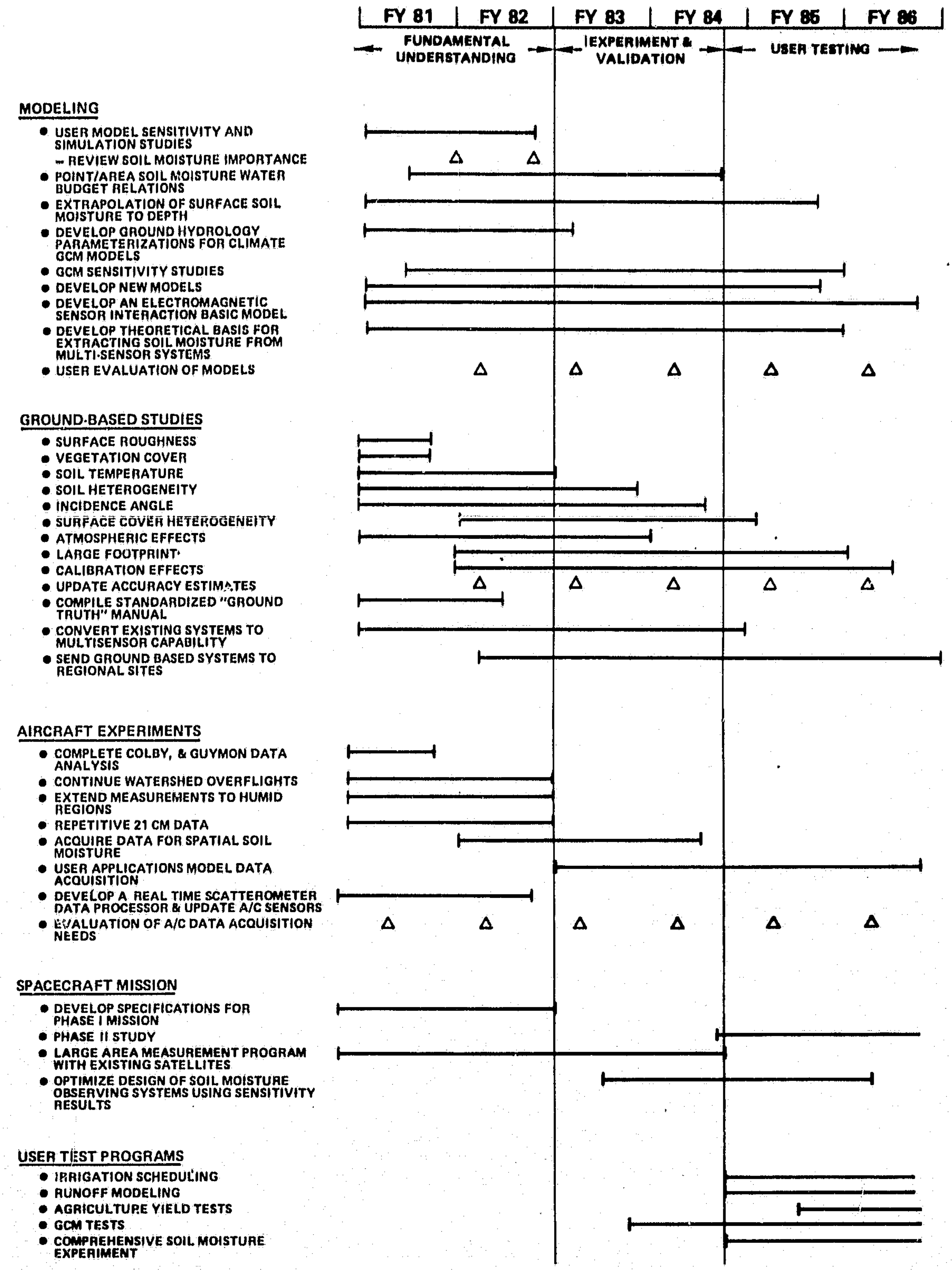

Figure 14. Schedule with Milestones.

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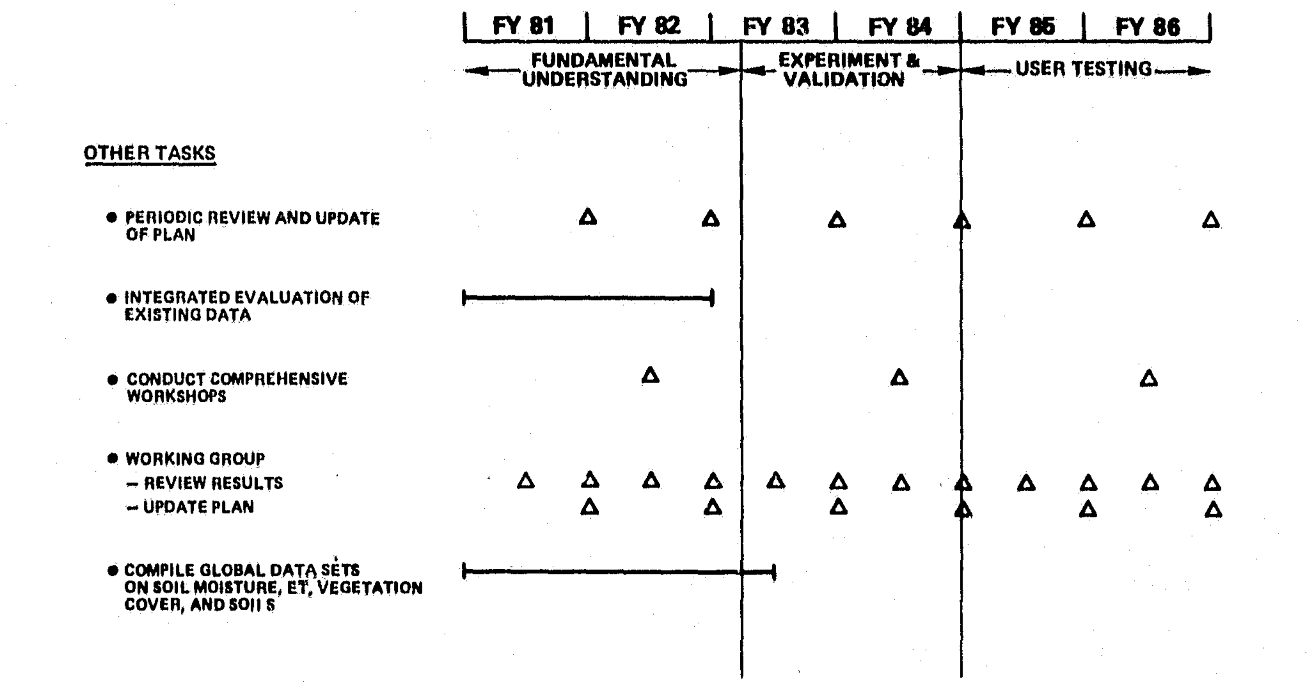

Figure 14. Schedule with Milestones (Continued).

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Table 9
Soil Moisture Experiments

Experiment Title	Objectives/Tasks	Location	Duration	Ground Truth/Elements
Humid Area Extension	(1) To extend the techniques for estimating soil moisture to humid areas to compare with arid and semi-arid regions	Tifton, GA Oxford, MS PA, OH, FL, GA, MS Midwestern Eastern US	2-3 years	Soil moisture with depth and area according to ground truth manual
	(2) Conduct 2 comprehensive data collection periods in humid area watersheds where water table intersects ground surface	FL/GA	1 month each for field work	Soil moisture with depth and area according to ground truth manual
User Applications Model Experiment	Work with other agency scientists to test soil moisture remote sensing methods for their particular applications. Evaluate the value of microwave inputs to user models, recognizing that individual user requirements may be different			As required for individual models (soil moisture at varying depths, soil texture, soil temperature, vegetation type, vegetation amount, crop yield, precipitation)
	(1) Simulate soil/water, and plant/atmosphere relationship emphasizing inputs from remote sensors	TBD	1979-1984	
	(2) Evaluate and modify a limited number of user models for demonstration of the advantage of remote sensing	TBD	1982-1984	

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Table 9
Soil Moisture Experiments (Continued)

Experiment Title	Objectives/Tasks	Location	Duration	Ground Truth/Elements
User Applications Model Experiment (Con't)	(3) Develop and evaluate comprehensive radiation transfer models for simultaneous multispectral simulation	TBD	1980-1984	
	(4) Extend and evaluate models spatially and temporally	TBD	1981-1984	
Areal Soil Comparison	(1) Determine the relationship between areal averaged and point measurements of soil moisture	Yuma, AR or Davis, CA	2 years	Follow manual for intensive depth and area measurements of soil moisture in an area where conventional soil moisture monitoring is being done
	(2) Correlate soil moisture obtained from gamma ray flights over extended areas with footprint determinations of soil moisture from spacecraft	Luverne, MN	1980-1982	Gamma ray flights must be scheduled to cover specific areas rather than linear ground paths
	(3) Define rainfall distribution patterns between rain gauge stations	In an area where good rain gauge data are available	1980-1982	Gridded rain gauge data soil moisture (0-15 cm)

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Table 9
Soil Moisture Experiments (Continued)

Experiment Title	Objectives/Tasks	Location	Duration	Ground Truth/Elements
Ground-Based Study of Factors Affecting Soil Moisture Determination				
(1) Effects of soil roughness (bare soil)	Minimize roughness, increase soil moisture sensitivity	Texas, Kansas, Beltsville, Santa Barbara Co. TBD	1979-1981	Soil moisture (0-15 cm)
(2) Effects of soil texture (bare soil)	Evaluate the sensitivity of microwave soil moisture response to soil type	Texas, Kansas, Beltsville, Santa Barbara Co. TBD	1979-1981	Soil moisture (0-15 cm)
(3) Effect of soil moisture profile layering	Determine effect of soil moisture layers on penetration depth on water sensitivity	Texas, Kansas, Beltsville, Santa Barbara Co. TBD	1980-1981	Soil moisture by horizons (0-15 cm)
(4) Subtasks effects of vegetation cover on experiments 1, 2 and 3 above	Determine vegetative effect on above variables, establish coefficients for vegetation	TBD	1981-1982	Soil moisture plus biomass (green, dry) plant height, ground cover, etc.

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Table 9
Soil Moisture Experiments (Continued)

Experiment Title	Objectives/Tasks	Location	Duration	Ground Truth/Elements
(5) Effect of diurnal variations on microwave & thermal estimates of soil moisture	Establish information for best overflight time and evaluate rapid temperature changes for estimating soil moisture	TBD	1980-1982	Soil moisture (root zone) air temperature
(6) Determine effects of snow cover	Establish effect of snow cover on remotely sensed soil moisture estimate	Area where snow cover variables exist (e.g., Luverne, MN)	1980-1982	Snow depth Snow H_2O content Soil Moisture (0-15 cm)
Comprehensive Soil Moisture Experiment	Collection and analysis of complete set of spectral data (reflected solar, infrared and microwave) for an entire growing season for various crops	Yuma, AR	6-8 months	Helicopter truth and sampling, intensive time sampling, all wave lengths, etc.

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APPENDIX A

NASA-FUNDED
AgRISTARS AND
RTOP PROJECTS

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FY 1980 AgRISTARS SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	681-05-02
TASK TITLE	:	(01) REMOTE SENSOR FIELD MEASUREMENTS
AFFILIATION/ INVESTIGATOR	:	GSFC/SCHMUGGE, UK/ULABY, TAMU/NEWTON, UA/WAITE, GSFC/WANG, SEA-AR/ENGMAN, JSC/PARIS & FENNER, JPL/NJOKU
OBJECTIVES	:	(A) ACQUISITION OF FIELD DATA TO STUDY THE PERTURBING EFFECTS OF SURFACE ROUGHNESS, VEGETATION AND SOIL TEMPERATURE ON THE VARIOUS SENSING APPROACHES (B) UPDATE THE UNIVERSITY OF KANSAS TRUCK SYSTEM BY ADDING A SUITABLE RADIOMETRIC CAPABILITY TO THEIR ACTIVE MICROWAVE SYSTEM
LOCATION	:	UNIVERSITY OF KANSAS - ACTIVE MICROWAVE TEXAS A&M - PASSIVE MICROWAVE UNIVERSITY OF ARKANSAS - BISTATIC RADAR GSFC/SEA - PASSIVE MICROWAVE JSC - ACTIVE MICROWAVE JPL/UCSB - PASSIVE MICROWAVE
GROUND TRUTH	:	AT HOME BASES OF THE GROUPS DOING THE FIELD EXPERIMENTS, MEASUREMENTS THROUGH THE GROWING SEASON
ELEMENTS OF THE STUDY	:	(A) DATA TYPES - MICROWAVE; X TO P BANDS; ACTIVE AND PASSIVE MSS, PHOTOGRAPHY (B) PLATFORMS/SENSORS - ALL DATA FROM TRUCK-MOUNTED SENSORS

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FY 1980 AgRISTARS SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	681-05-03
TASK TITLE	:	(01) REMOTE SENSOR AIRCRAFT MEASUREMENTS
AFFILIATION/ INVESTIGATOR	:	GSFC/SCHMUGGE JSC/PARIS
OBJECTIVES	:	TO BE DETERMINED BASED ON THE ANALYSIS OF DATA ACQUIRED DURING THE 1978 FLIGHTS OVER GUYMAN, OKLAHOMA, AND COLBY, KANSAS
LOCATION	:	USDA-SEA/AR RESEARCH WATERSHEDS IN OKLAHOMA AND GEORGIA
GROUND TRUTH	:	COMPREHENSIVE SM SAMPLES OVER AN EXTENSIVE AREA CONCURRENT WITH A/C INSTRUMENTATION OVERFLIGHT
ELEMENTS OF THE STUDY	:	AIRCRAFT NASA C-130 - WIDE RANGE OF SENSORS

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FY 1980 AgRISTARS SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	681-05-04
TASK TITLE	:	(01) INFORMATION EXTRACTION ANALYSIS
AFFILIATION/ INVESTIGATOR	:	UK/ULABY, UA/WAITE, TAMU/NEWTON, GSFC/SCHMUGGE, JSC/PARIS, JPL&UCSB/NJOKU
OBJECTIVES	:	(A) A PRELIMINARY SPECIFICATION OF THE PARAMETERS FOR A SPACE SYSTEM TO REMOTELY SENSE SOIL MOISTURE (B) DEVELOP A SET OF CANDIDATE ALGORITHMS FOR USING REMOTELY SENSED MULTISENSOR DATA TO ESTIMATE THE SOIL MOISTURE DISTRIBUTION (3-DIMENSIONAL) IN THE SURFACE LAYER OF SOILS (C) AN ASSESSMENT OF THE ACCURACY OF THE ESTIMATES THAT CAN BE EXPECTED WITH THESE ALGORITHMS (D) ANALYSIS OF DATA FROM EXISTING SPACEBORNE SYSTEMS, E.G., SEASAT SAR FOR INFORMATION RELATING TO SOIL MOISTURE
LOCATION	:	NA
GROUND TRUTH	:	USE EXISTING DATA SETS
ELEMENTS OF THE STUDY:		MODELING

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FY 1980 AgRISTARS SOIL MOISTURE RESEARCH

INVESTIGATION NO. : 681-05-04

TASK TITLE : (04) COMPARATIVE TESTING OF ROOT ZONE SOIL MOISTURE MODELS

AFFILIATION/ INVESTIGATOR : JSC/PARIS

OBJECTIVES : TO DETERMINE THE BEST MODEL OR MODELS:

(A) TO REPRESENT GROUND TRUTH (SM PROFILE) FOR REMOTE SENSING INVESTIGATIONS
(B) TO BE A SUBMODEL FOR YIELD MODELS DRIVEN BY RS SURFACE ZONE SM DATA

LOCATION : MANY SITES REPRESENTING A RANGE OF SOIL AND CLIMATE CONDITIONS ARE NEEDED

GROUND TRUTH : NA

ELEMENTS OF THE STUDY: MODELING

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FY 1980 AgRISTARS SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	681-05-04
TASK TITLE	:	(05) SPATIAL VARIABILITY
AFFILIATION/ INVESTIGATOR	:	USDA/ENGMAN
OBJECTIVES	:	(A) THE CURRENT DATA BASE (USDA AND NASA) SHOULD BE EVALUATED TO DETERMINE GENERAL RELATIONSHIPS BETWEEN POINT SOIL MOISTURE AND SPATIAL AVERAGES AS A FUNCTION OF COVER, SOIL AND CLIMATIC CONDITIONS, AND VARIABILITY OF SOIL PHYSICAL PROPERTIES (B) EVALUATE SPATIAL RAINFALL PATTERNS
LOCATION	:	WATERSHEDS IN RIESEL, TEXAS; CHICKASHA, OKLAHOMA; TIFTON, GEORGIA; OKEECHOBEE, FLORIDA; AND HAND COUNTY, SOUTH DAKOTA. RAIN GAUGE NETWORKS IN: CHICKASHA, OKLAHOMA (USDA); CENTRAL MONTANA; NORTHWEST KANSAS; HIGH PLAINS OF TEXAS (USDI BUREAU OF RECLAMATION); AND ILLINOIS STATE WATER SURVEY. OTHER POSSIBLE SITES: PHOENIX, ARIZONA AND COLBY COUNTY, KANSAS
GROUND TRUTH	:	INTENSIVE NETWORK OF RAIN GAUGES
ELEMENTS OF THE STUDY:		TRUCK, AIRCRAFT, SATELLITE AND RAIN GAUGE DATA

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FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO. : 677-22-02

TASK TITLE : (1) ADVANCED MICROWAVE SOIL MOISTURE STUDIES

AFFILIATION/ INVESTIGATOR : GSFC/SCHMUGGE

OBJECTIVE : STUDY PASSIVE MICROWAVE SOIL MOISTURE SENSING APPROACHES; PRIMARILY P-BAND RESPONSES IN RELATION TO RADIATIVE TRANSFER MODELS

LOCATION : BELTSVILLE AGRICULTURAL RESEARCH CENTER

GROUND TRUTH : GROUND TRUTH DATA WILL INCLUDE: SOIL MOISTURE AT DEPTHS 0-2.5 CM, 2.5-5 CM, 5-10 CM, 10-15 CM, SOIL TEMPERATURES, SOIL CHARACTERISTICS AND ROUGHNESS

ELEMENTS OF THE STUDY:

- MODELS
- TRUCK
  - TIR
  - PM

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FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	677-22-02
TASK TITLE	:	(2) ADVANCED MICROWAVE SOIL MOISTURE STUDIES
AFFILIATION/ INVESTIGATOR	:	SDSU/MYERS
OBJECTIVE	:	ANALYZE DATA FROM MULTIPLE AIRCRAFT FLIGHTS TO DETERMINE THE PRESENCE OF NEAR-SURFACE AQUIFERS
LOCATION	:	SOUTHEASTERN SOUTH DAKOTA
GROUND TRUTH	:	SURFACE SOIL MOISTURE AND THE DEPTH TO THE WATER TABLE

ELEMENTS OF THE STUDY:

- MODELS
- AIRCRAFT
  - VIS (CIR)
  - TIR (PRT-5)
  - PM (L-BAND)

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FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	677-22-06
TASK TITLE	:	(2) INFORMATION CONTENT STUDIES; SOIL MOISTURE/MICROWAVE
AFFILIATION/ INVESTIGATOR	:	GSFC/SCHMUGGE, CHANG TAMU/ -
OBJECTIVE	:	DETERMINE CAPABILITIES OF PASSIVE AND ACTIVE MICROWAVE DATA TO IMPROVE RUNOFF FORECASTS AND WATER MANAGEMENT
LOCATION	:	USDA WATERSHEDS • CHICKASHA, OK • RIESEL, TX
GROUND TRUTH	:	SOIL MOISTURE, VEGETATION, AND OTHER SELECTED INFORMATION REQUIRED TO SUPPLEMENT THE MICROWAVE DATA STUDIES
ELEMENTS OF THE STUDY:		• MODELS • AIRCRAFT - VIS (CIR B/W) - TIR (PRT-5) - AM (SCAT) - PM (PMIS, MFMR)

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FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	677-22-06
TASK TITLE	:	(4) INFORMATION CONTENT STUDIES; WATER RESOURCES/THERMAL AND HIGH RESOLUTION DATA
AFFILIATION/ INVESTIGATOR	:	GSFC/PRICE, SALOMONSON
OBJECTIVE	:	EXAMINE THE APPLICABILITY OF HIGH RESOLUTION SPACECRAFT THERMAL AND VISIBLE BAND DATA TO WATER RESOURCES MANAGEMENT SITUATIONS
LOCATION	:	SELECTED STUDY AREAS (SOUTHEASTERN SOUTH DAKOTA)
GROUND TRUTH	:	CONVENTIONAL METEOROLOGICAL AND WATER RESOURCES DATA AND OTHER AVAILABLE INFORMATION SOURCES

ELEMENTS OF THE STUDY:

- MODELS
- AIRCRAFT
  - VIS (TM SIMULATOR)
  - TIR (TM SIMULATOR)
- SPACECRAFT
  - VIS (HCMM, MSS)
  - TIR (HCMM, AVHRR, MSS)

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FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO. : 677-22-07

TASK TITLE : (1) HYDROLOGIC MODELING STUDIES; EVALUATE THE USE OF MICROWAVE DATA FOR WATER RESOURCES APPLICATIONS

AFFILIATION/ INVESTIGATOR : GSFC/SCHMUGGE
USDA/JACKSON
U OF MD/BELL

OBJECTIVES :

- DEVELOP A PREDICTIVE MODEL FOR SOIL MOISTURE BASED ON THE SCIENCE AND EDUCATION ADMINISTRATION (SEA) WATER BALANCE MODEL
- EVALUATE THE USE OF REMOTELY SENSED SOIL MOISTURE DATA IN SOIL MOISTURE MODELS

LOCATION : USDA WATERSHEDS

- CHICKASHA, OK
- RIESEL, TX
- TIFTON, GA
- OKEECHOBEE, FL

GROUND TRUTH : SOIL MOISTURE DATA: 0-2 CM, 2-5 CM, 5-15 CM, AND 15 CM TO DEPTH OF WATER TABLE IF LESS THAN 1 M. APPROXIMATELY 10 SAMPLES WILL BE TAKEN FOR EACH 100 x 600 FT. SITE

ELEMENTS OF THE STUDY:

- MODELS
- AIRCRAFT
  - VIS (CIR, MSS)
  - TIR (PRT-5)
  - AM (SCAT)
  - PM (PMIS, MFMR)

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FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	677-22-07
TASK TITLE	:	(3) HYDROLOGIC MODELING STUDIES; REMOTE SENSING OF RUNOFF COEFFICIENTS
AFFILIATION/ INVESTIGATOR	:	GSFC/CHANG TAMU/BLANCHARD
OBJECTIVES	:	COMPARE SCATTEROMETER AND SAR RESPONSE DERIVED RUNOFF COEFFICIENTS WITH CONVENTIONALLY ACQUIRED COEFFICIENTS FOR SMALL SUBWATERSHED AREAS
LOCATION	:	USDA WATERSHEDS • CHICKASHA, OK • RIESEL, TX
GROUND TRUTH	:	CONVENTIONAL SOIL MOISTURE PARAMETERS (I.E., MOISTURE COVER, SLOPE, SOILS, ROUGHNESS, TEMPERATURE, ETC.) WILL BE GATHERED OVER THE SITES
ELEMENTS OF THE STUDY:		• MODELS • AIRCRAFT - VIS (CIR) - AM (SCAT)

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FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO. : 677-22-07

TASK TITLE : (5) HYDROLOGIC MODELING STUDIES; MODELING OF THERMAL IR DATA FOR EVAPOTRANSPIRATION

AFFILIATION/ INVESTIGATOR : GSFC/PRICE

OBJECTIVES : USE ROSEMA SOIL MOISTURE MODEL TO RELATE THERMAL IR ALBEDO, AND MICROWAVE DATA TO DETERMINE EVAPOTRANSPIRATION

LOCATION : SELECTED STUDY AREAS

GROUND TRUTH : MODEL RESULTS WILL EVENTUALLY BE COMPARED TO SOIL MOISTURE FIELD OBSERVATIONS

ELEMENTS OF THE STUDY:

- MODELS
- SPACECRAFT
  - VIS
  - TIR
  - PM

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FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	677-22-08
TASK TITLE	:	(1) REMOTE SENSING OF SOIL MOISTURE FOR WATER RESOURCES
AFFILIATION/ INVESTIGATOR	:	GSFC/SCHMUGGE
OBJECTIVES	:	ACQUISITION AND ANALYSIS OF AIRCRAFT MICROWAVE DATA FOR DETERMINING THE CAPABILITIES OF THESE SYSTEMS FOR REMOTE SENSING OF SOIL MOISTURE. THESE RESULTS WILL BE COMBINED WITH FIELD MEASUREMENTS AND MODEL RESULTS TO DETERMINE THE EFFECTS OF VEGETATIVE COVER AND SURFACE ROUGHNESS
LOCATION	:	HAND COUNTY, SOUTH DAKOTA
GROUND TRUTH	:	SOIL MOISTURE MEASUREMENTS COINCIDENT WITH AIRCRAFT FLIGHTS WILL INCLUDE: MOISTURE AND TEMPERATURE AT DEPTHS 0-2.5 CM, 2.5-5 CM, 5-10 CM. SAMPLES WILL BE TAKEN AT A DENSITY OF 24 SAMPLES/MILE OVER 20-30 SITES

ELEMENTS OF THE STUDY:

- MODELS
- AIRCRAFT
  - VIS (CIR)
  - TIR (PRT-5)
  - PM (DMIS, MFMR)

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FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	677-22-10
TASK TITLE	:	(1) SEASAT EXPERIMENTS; RUNOFF COEFFICIENTS
AFFILIATION/ INVESTIGATOR	:	GSFC/CHANG TAMU/BLANCHARD
OBJECTIVES	:	IDENTIFY SAR AND OTHER SPACECRAFT RELATIONSHIPS RELATIVE TO THE DERIVATION OF RUNOFF COEFFICIENTS
LOCATION	:	GUYMON, OK
GROUND TRUTH	:	DETAILED SOIL MOISTURE DATA FOR FOUR SITES (APPROXIMATELY 160 ACRES EACH) WILL BE SUPPLEMENTED WITH CONVENTIONAL METEOROLOGICAL OBSERVATIONS

ELEMENTS OF THE STUDY:

- AIRCRAFT
  - VIS (CIR, B/W, M^2S)
  - TIR (M^2S)
  - AM (SCAT)
  - PM (PMIS, MFMR)
- SPACECRAFT
  - VIS (MSS)
  - TIR (MSS)
  - AM (SAR)

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FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	677-22-10
TASK TITLE	:	(2) SEASAT EXPERIMENTS; SOIL WETNESS
AFFILIATION/ INVESTIGATOR	:	GSFC/CHANG UCSB/ESTES
OBJECTIVES	:	ANALYZE COLLECTED DATA AND PERFORM STATISTICAL ANALYSES TO RELATE SEASAT-SAR BACKSCATTER CROSS SECTIONS SOIL WETNESS, ROUGHNESS AND SURFACE COVER
LOCATION	:	GUYMON, OK
GROUND TRUTH	:	DETAILED SOIL MOISTURE DATA FOR FOUR SITES (APPROXIMATELY 160 ACRES EACH) WILL BE SUPPLEMENTED WITH CONVENTIONAL METEOROLOGICAL OBSERVATIONS

ELEMENTS OF THE STUDY:

- AIRCRAFT
  - VIS (CIR, B/W, M^2S)
  - TIR (M^2S)
  - AM (SCAT)
  - PM (PMIS, MFMR)
- SPACECRAFT
  - AM (SAR)

FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO. : 677-22-13

TASK TITLE : (1) SOIL MOISTURE MODELING

AFFILIATION/ INVESTIGATOR : ERT INC./BURKE

OBJECTIVES :

- ANALYSIS OF THERMAL IR AND MICROWAVE AIRCRAFT DATA TAKEN OVER PHOENIX IN 1975 FOR COMPARISONS WITH RADIATIVE TRANSFER MODELS
- IDENTIFY THE ABILITY OF MULTIPLE WAVELENGTH COMBINATIONS TO PROVIDE SOIL MOISTURE INFORMATION AS COMPARED WITH SINGLE WAVELENGTH DERIVED PARAMETERS

LOCATION : PHOENIX, AZ

GROUND TRUTH : DETAILED SOIL MOISTURE AND TEMPERATURE PROFILES AT LEVELS 0-1 CM, 1-2 CM, 2-5 CM, 5-9 CM, 9-15 CM. FROM 50 TO 100 FIELDS WILL BE SAMPLED WITH APPROXIMATELY 4 SAMPLES TAKEN ON EACH 40 ACRES

ELEMENTS OF THE STUDY:

- MODELS
- AIRCRAFT
  - VIS (CIR)
  - TIR (PRT-5)
  - PM (PMIS, MFMR)

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FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO. : 677-22-14

TASK TITLE : (1) SOIL MOISTURE INTEGRATED PLAN FORMULATION

AFFILIATION/INVESTIGATOR : GSFC/RANGO, SCHMUGGE

OBJECTIVES :
- CREATE A FIVE YEAR NASA PLAN FOR SOIL MOISTURE RESEARCH
- CONDUCT PERIODIC MEETINGS OF THE SOIL MOISTURE WORKING GROUP

LOCATION : GSFC

GROUND TRUTH : NA

ELEMENTS OF THE STUDY: PROGRAM PLANNING

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FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	677-22-23
TASK TITLE	:	(1) SPACECRAFT THERMAL DATA ANALYSIS FOR IRRIGATION SCHEDULING
AFFILIATION/ INVESTIGATOR	:	GSFC/SALOMONSON
OBJECTIVES	:	EVALUATE SATELLITE THERMAL DATA TO DETERMINE THEIR UTILITY SCHEDULING IN IRRIGATION
LOCATION	:	WELLTON-MOHAWK-GILA PROJECT
GROUND TRUTH	:	GROUND-BASED DATA SETS
ELEMENTS OF THE STUDY:		• SPACECRAFT - TIR

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FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	677-22-23
TASK TITLE	:	(2) LANDSAT DATA
AFFILIATION/ INVESTIGATOR	:	GSFC/SALOMONSON
OBJECTIVES	:	EVALUATE THE USE OF LANDSAT DATA AND POSSIBLY HCMM DATA AS INPUT TO A MODEL THAT ESTIMATES CROP WATER NEEDS
LOCATION	:	WELLTON-MOHAWK-GILA
GROUND TRUTH	:	WEATHER ELEMENTS (SOLAR RADIATION, TEMPERATURE, AND PRECIPITATION)

ELEMENTS OF THE STUDY:

- SPACECRAFT
  - LANDSAT
  - HCMM

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FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	677-22-23
TASK TITLE	:	(3) PLANT STRESS
AFFILIATION/ INVESTIGATOR	:	GSFC/TUCKER
OBJECTIVES	:	EVALUATE THE UTILITY OF MIDDLE INFRARED OBSERVATIONS FOR DETECTING PLANT STRESS CAUSED BY WATER DEFICIENCY
LOCATION	:	BELTSVILLE, MARYLAND AGRICULTURE RESEARCH CENTER
GROUND TRUTH	:	FIELD RADIOMETER DATA
ELEMENTS OF THE STUDY	:	FIELD RADIOMETERS

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FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	677-39-05
TASK TITLE	:	(1) EVALUATE CURRENT STATE OF THE ART FOR SOIL MOISTURE DETERMINATION FROM REMOTE SENSING SYSTEMS
AFFILIATION/ INVESTIGATOR	:	GSFC/SCHMUGGE
OBJECTIVES	:	DETERMINE CURRENT STATE OF THE ART IN SOIL MOISTURE SENSING WITH MICROWAVE AND THERMAL INFRARED TECHNIQUES
LOCATION	:	UNIVERSITIES OF MISSOURI AND KANSAS
GROUND TRUTH	:	FIELD RADIOMETER DATA
ELEMENTS OF THE STUDY	:	MICROWAVE SYSTEMS

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FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	577-39-05
TASK TITLE	:	(2) PHASE A STUDY OF SOIL MOISTURE MISSION
AFFILIATION/ INVESTIGATOR	:	GSFC
OBJECTIVES	:	USE RESULTS OF THE ELEMENT 1 STUDIES TO DEVELOP A CANDIDATE SPACE SYSTEM FOR A SOIL MOISTURE MISSION
LOCATION	:	GSFC
GROUND TRUTH	:	NA
ELEMENTS OF THE STUDY:		ELEMENT 1 STUDY

FY 1980 NASA SOIL MOISTURE RESEARCH

INVESTIGATION NO.	:	146-10-03
TASK TITLE	:	SOIL MOISTURE/MOISTURE TRANSPORT PROCESSES (AN)
AFFILIATION/ INVESTIGATOR	:	GSFC/HALEM, UNIVERSITY OF CONNECTICUT/LIN
OBJECTIVES	:	STUDY THE SEASONAL CHANGES OF SOIL MOISTURE AND THE INTERACTIVE MOISTURE TRANSPORT PROCESSES IN ARID AND SEMI-ARID REGIONS BY MEANS OF HYDROLOGICAL MODELING USING A DETERMINISTIC, PHYSICALLY-BASED APPROACH
LOCATION	:	N/A
GROUND TRUTH	:	ASSIMILATION OF DATA PERTINENT TO MODEL VERIFICATION
ELEMENTS OF THE STUDY:		MODELING

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APPENDIX B

HCMM EXPERIMENTS

HEAT CAPACITY MAPPING MISSION - SOIL MOISTURE INVESTIGATIONS

Number	Task	Affil./ Investigator	Title	Study Objectives	Location	Ground Truth	Elements of the Study: Models	Truck TIR	Truck AM	Truck PM	Aircraft VIS	Aircraft TIR	Aircraft AM	Aircraft PM	Spacecraft VIS	Spacecraft TIR	Spacecraft AM	Spacecraft PM
HCM-002	1	USDA/ Wiegand	Plant Cover, Soil Temperature Freeze, Water Stress, and Evapotranspiration Conditions	Use of optimum day and night HCMM data for freeze damage assessment, planting data advisory, and evapotranspiration calculations	South Texas	Continuous measurements of solar radiation, total hemispherical radiation wind movements, air temperature, vapor pressure, and soil temperature for wet and dry plots	X				X	X			X	X		
HCM-005	1	USDA/ Jackson	Remote Detection of Soil Moisture Using Data from the Heat Capacity Mapping Mission	To demonstrate the usefulness of soil temperature and albedo data measured from a space platform in assessing soil moisture over large areas for the purpose of improving agricultural resources management practices	California	Ground measurements to include: Soil moisture, Albedo, Meteorological parameters	X				X	X			X	X		
HCM-032	1	SDSU/ Moore	HCMM Energy Budget Data as a Model Input for Assessing Regions of High Potential Groundwater Pollution	Development of a remote sensing method for rapid and accurate detection and monitoring of regions with shallow water tables which are susceptible to groundwater contamination	South Dakota	Soil temperatures at 10 cm, 50 cm, 100 cm, and 150 cm depths measured with thermocouples for ten test sites selected on the basis of water table depth, aquifer thickness, groundwater flow rate, and land use	X				X	X			X	X		
HCM-045	1	NOAA/ Wiesnet	Applications of HCMM Data to Soil Moisture, Snow, and Estuarine Current Studies	Charting of tidal currents in estuaries; evaluation of thermal inertia soil moisture measurements; study of the thermal emission of snow	Potomac R., MD; Cooper R., SC; Cranberry Lake, NY; Luverne, MN	Data to include: Conventional meteorological observations; Radiant temperature of snow, trees, and exposed surfaces; Soil Moisture; Thermal inertia maps					X	X			X	X		
					California										X	X		
HCM-049	1	TAMU/ Harlan	Plant Canopy Temperature and Soil Moisture Experiment	Demonstrate the feasibility of utilizing HCMM-derived plant canopy temperature and soil moisture data as a measure of cultivated crop condition in dryland farming areas where temperature and precipitation measurement do not exist	Oklahoma	Measurements of: Soil moisture, Precipitation, Air temperature, Soil temperature, Canopy temperature	X				X	X			X	X		
					Kansas													
HCM-054	1	CCRS/ Cihlar	Soil Moisture Estimating in Agricultural Areas from Thermal Emission Measurements	To evaluate the usefulness of the thermal inertia concept to estimate soil moisture from remote sensing measurements	Canada	Ground information describing soil, plant and atmospheric conditions: Soil - soil type, surface roughness, water content for two layers (0-2 cm, 2-4 cm), physical temperature at three depths (0 cm, 2 cm, 4 cm), and infrared temperature (0 cm); Plants - type, height, coverage; Atmosphere - temperature, humidity, cloud cover, precipitation etc.									X	X		

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HCMM INVESTIGATION
(HCM-002)

TITLE	:	FREEZE DAMAGE ASSESSMENT, PLANTING DATA ADVISORY, AND EVAPOTRANSPIRATION
PRINCIPAL INVESTIGATOR	:	CRAIG L. WIEGAND
AFFILIATION	:	USDA-ARS-WESLACO, TX
DISCIPLINE AREA(S)	:	FREEZE DAMAGE SOIL MOISTURE AND WATER LAND TEMP GRADIENTS
OBJECTIVES	:	USE OF OPTIMUM DAY AND NIGHT HCMM DATA FOR FREEZE DAMAGE ASSESSMENT, PLANTING DATA ADVISORY, AND EVAPOTRANSPIRATION
APPROACH	:	ANALYSIS OF HCMM DATA IN RELATION TO GROUND TRUTH AND AIRCRAFT-OBTAINED DATA. CONTINUOUS MEASUREMENTS OF SOLAR RADIATION, TOTAL HEMISPHERICAL RADIATION, WIND MOVEMENTS, AIR TEMPERATURE, VAPOR PRESSURE, AND SOIL TEMPERATURE IN WET AND DRY PLOTS WILL BE OBTAINED
ANTICIPATED RESULTS	:	IDENTIFY AREAS OF LEAST FREEZE HAZARD FOR GROWING TEMPERATURE-SENSITIVE CROPS. MAXIMIZE HARVESTABLE YIELD FROM FREEZE-DAMAGED CROPS. ASSESS FREEZE DAMAGE TO CITRUS RELATIVE TO HCMM DATA. RELATE HCMM TEMP. VS SOIL WATER DEPLETION AND DAYS SINCE IRRIGATION. DETERMINE WHETHER CANOPY TEMPERATURE DIFFERS CHARACTERISTICALLY AMONG CROPS. RELATE NIGHTTIME SOIL TEMPERATURE TO MAJOR SOIL TEXTURE VARIATIONS OVER THE RIO GRANDE VALLEY.

TEST SITE(S)	:	LOCATION	COORDINATES
		TEXAS	28°N 100°W, 27°N 97°W, 26°30'N 97°W, 26°30'N 100°W

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HCMM INVESTIGATION
(HCM-005)

TITLE	:	REMOTE DETECTION OF SOIL MOISTURE USING DATA FROM HCMM
PRINCIPAL INVESTIGATOR	:	RAY D. JACKSON
AFFILIATION	:	U. S. WATER CONSERVATION LAB, ARS, USDA, PHOENIX, AZ
DISCIPLINE AREA(S)	:	SOIL MOISTURE, PLANT CANOPY
OBJECTIVES	:	TO DEMONSTRATE THE USEFULNESS OF SOIL TEMPERATURE AND ALBEDO DATA MEASURED FROM A SPACE PLATFORM IN ASSESSING SOIL MOISTURE OVER LARGE AREAS FOR THE PURPOSE OF IMPROVING AGRICULTURAL RESOURCES MANAGEMENT PRACTICES
APPROACH	:	TO USE MULTILEVEL SAMPLING TO EVALUATE THE FEASIBILITY OF TRANSFERRING GROUND PROVEN METHODS FOR MEASURING SOIL MOISTURE TO SPACECRAFT USE. GROUND TRUTH AND AIRBORNE MEASUREMENTS OF REFLECTED SUNLIGHT AND INFRARED RADIANCES WILL PROVIDE THE BASIS FOR INTERPRETING THE SPACECRAFT DATA.
ANTICIPATED RESULTS	:	DEMONSTRATION OF THE ABILITY TO DETECT AND MONITOR SOIL MOISTURE FROM SPACE, AND MAPS OF SOIL MOISTURE AND SOIL TEMPERATURE

TEST SITE(S) :

LOCATION	COORDINATES
CALIFORNIA	38°45'N, 122°05'W

HCMM INVESTIGATION
(HCM-032)

TITLE	:	HCMM ENERGY BUDGET DATA AS A MODEL INPUT FOR ASSESSING REGIONS OF HIGH POTENTIAL GROUNDWATER POLLUTION
PRINCIPAL INVESTIGATOR	:	D. G. MOORE
AFFILIATION	:	REMOTE SENSING INSTITUTE, SOUTH DAKOTA STATE UNIVERSITY
DISCIPLINE AREA(S)	:	ENVIRONMENTAL QUALITY, WATER RESOURCES, AGRICULTURE
OBJECTIVES	:	DEVELOPMENT OF A REMOTE SENSING METHOD FOR RAPID AND ACCURATE DETECTION AND MONITORING OF REGIONS WITH SHALLOW WATER TABLES WHICH ARE SUSCEPTIBLE TO GROUNDWATER CONTAMINATION
APPROACH	:	TEN "INTENSIVE" TEST SITES WILL BE SELECTED ON THE BASIS OF WATER TABLE DEPTH, AQUIFER THICKNESS, GROUNDWATER FLOW RATE AND LAND USE. SOIL TEMPERATURES WILL BE MEASURED WITH THERMOCOUPLES, AND DATA RELATED TO HCMM, LANDSAT AND AIRCRAFT INFORMATION
ANTICIPATED RESULTS	:	THERMAL INERTIA, TEMPERATURE, ALBEDO INFORMATION WILL BE USED TO PREDICT WATER TABLE DEPTHS AND OTHER AQUIFER PROPERTIES WHICH CAN BE USED TO LOCATE REGIONS HAVING A HIGH POTENTIAL FOR GROUNDWATER CONTAMINATION

TEST SITE(S) :

LOCATION	COORDINATES				
EASTERN SOUTH DAKOTA	46:00N 101:00W	42:30N 96:25W	42:30N 98:00W	46:00N 95:30W	42:30N 95:30W

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HCMM INVESTIGATION
(HCM-045)

TITLE : APPLICATIONS OF HCMM DATA TO SOIL MOISTURE, SNOW AND ESTUARINE CURRENT STUDIES

PRINCIPAL INVESTIGATOR: DONALD R. WIESNET

AFFILIATION : NOAA/NESS ENVIRONMENTAL SCIENCES GROUP

DISCIPLINE AREA(S) : HYDROLOGY, WATER RESOURCES, OCEANOGRAPHY

OBJECTIVES : CHART TIDAL CURRENTS IN ESTUARIES, THERMAL INERTIA, SOIL MOISTURE MEASUREMENTS/THERMAL EMISSION OF SNOW

APPROACH : COMPARISON OF HCMM DATA ANALYSES WITH GROUND TRUTH

ANTICIPATED RESULTS : SYNOPTIC TIDAL CURRENT CHARTS; EVALUATION OF CONTAMINATION OF THERMAL SIGNATURE OF SNOW BY FOREST COVER IN WINTER AND BY TYPE OF TREE

TEST SITE(S) :	LOCATION	COORDINATES
1	POTOMAC RIVER, MD	37°55'N - 38°35'N, 76° - 77°30'W
2	COOPER RIVER, SC	42°44' - 32°54'N, 79°50' - 80°W
3	CRANBERRY LAKE, NY	44°10'N - 74°30'W - 75°W
4	LUVERNE, MN	43°40'N, 96° - 96°30'W

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HCMM INVESTIGATION
(HCM-049)

TITLE : PLANT CANOPY TEMPERATURE AND SOIL MOISTURE EXPERIMENT

PRINCIPAL INVESTIGATOR: J. C. HARLAN

AFFILIATION : REMOTE SENSING CENTER, TEXAS A&M UNIVERSITY

DISCIPLINE AREA(S) : PLANT CANOPY TEMPERATURE & SOIL MOISTURE

OBJECTIVES : DEMONSTRATE THE FEASIBILITY OF UTILIZING HCMM-DERIVED PLANT CANOPY TEMPERATURE AND SOIL MOISTURE DATA AS A MEASURE OF CULTIVATED CROP CONDITION IN UNGAUGED DRYLAND FARMING AREAS WHERE TEMPERATURES AND PRECIPITATION MEASUREMENT DO NOT EXIST

APPROACH : HCMM DATA PROCESSING TO DETERMINE MEAN AND VARIANCE FOR LARGE DELINEATED AREAS FOLLOWED BY MULTIPLE REGRESSION ANALYSIS AGAINST GROUND TRUTH TO PROVIDE CORRELATION INFORMATION TOWARDS CREATION OF INPUTS TO CROP PRODUCTION MODELS

ANTICIPATED RESULTS : THE RELIABILITY OF HCMM-DERIVED PARAMETERS WILL BE DETERMINED

TEST SITE(S) :

	LOCATION	COORDINATES
1	OKLAHOMA	35:07N, 98:00W
2	KANSAS	39:20N 101:00W

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HCMM INVESTIGATION
(HCM-054)

TITLE	:	SOIL MOISTURE ESTIMATING IN AGRICULTURAL AREAS FROM THERMAL EMISSION MEASUREMENTS
PRINCIPAL INVESTIGATOR	:	JOS. CIHLAR
AFFILIATION	:	CANADA CENTRE FOR REMOTE SENSING
DISCIPLINE AREA(S)	:	SOIL MOISTURE STUDIES, AGRICULTURE
OBJECTIVES	:	TO EVALUATE THE USEFULNESS OF THE THERMAL INERTIA CONCEPT TO ESTIMATE SOIL MOISTURE FROM REMOTE SENSING MEASUREMENTS
APPROACH	:	SOIL MOISTURE STUDIES FROM REMOTELY SENSED DATA USING THE THERMAL INERTIA CONCEPT WILL BE USED TO PREPARE A MODEL FOR SPRING WHEAT YIELD PREDICTIONS. SOIL TYPE EFFECTS, ATMOSPHERIC CONDITIONS, SEASONAL EFFECT, CROP COVER, AIRCRAFT VS. SATELLITE MEASUREMENTS OF SAME SOIL TYPE WILL ALL BE ADDRESSED
ANTICIPATED RESULTS	:	ANSWERS WILL BE OBTAINED TO QUESTIONS REGARDING SOIL MOISTURE MEASUREMENT, SOIL TYPE EFFECTS, ENVIRONMENTAL (ATMOSPHERIC) EFFECTS, ALGORITHM DETERMINATION AND THERMAL INERTIA APPLICATIONS
TEST SITE(S)	:	

LOCATION	COORDINATES #1	COORDINATES #2
CANADA	54:00N, 121:00W	48:00N, 79:00W
	49:00N, 121:00W	46:00N, 79:00W
	49:00N, 107:00W	45:00N, 75:30W
	54:00N, 107:00W	45:00N, 71:30W
		47:00N, 71:30W
		49:00N, 73:00W